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## CONTENTS

Application of a Statistical Model to Simple Discrimination Learning in Human Subjects: W. K. ESTES AND C. J. BURKE ..... 81

Simultaneous Brightness Induction as a Function of Inducing- and Test-Field Luminances: E. G. HEINEMAN ..... 89

The Effect of Prior Training with a Scale of Distance on Absolute and Relative Judgments of Distance Over Ground: E. J. GIBSON, R. BERGMAN, AND J. PURDY ..... 97

Preferred Patterns of Motor and Verbal Responses: R. S. LINCOLN AND L. T. ALEXANDER 106

Retroactive and Proactive Effects Under Varying Conditions of Response Similarity: R. K. YOUNG 113

Studies of Distributed Practice: XIV. Intralist Similarity and Presentation Rate in Verbal-Discriminating Learning of Consonant Syllables: B. J. UNDERWOOD AND E. J. ARCHER 120

The Relation of Apparent Shape to Apparent Slant in the Perception of Objects: J. BECK AND J. J. GIBSON 125

Dark-Adaptation Luminance Thresholds for the Resolution of Detail Following Different Durations of Light Adaptation: A. L. DIAMOND AND A. S. GILINSKY ..... 134

Foveal Simultaneous Contrast as a Function of Inducing-Field Area: A. L. DIAMOND ... 144

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Journal of
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# APPLICATION OF A STATISTICAL MODEL TO SIMPLE DISCRIMINATION LEARNING IN HUMAN SUBJECTS[1]

W. K. ESTES AND C. J. BURKE

*Indiana University*

It is assumed by all S-R reinforcement theories that discrimination learning is compounded in a simple way from cumulative effects of reinforcement and nonreinforcement. If so, then whenever explicit laws of acquisition and extinction have been formulated for a given situation, the main facts of discrimination learning should be predictable from these laws without the addition of special hypotheses. In the present study we have tried to evaluate this assumption in a situation where the necessary preliminary analysis of elementary learning has been carried far enough to permit explicit predictions.

A series of recent experiments on simple human learning under random reinforcement (**1, 4, 8, 9**) have been interpreted with considerable success in terms of a theory which incorporates a statistical model of the stimulus situation and contiguity assumptions concerning the learning process. In these experiments *S*'s task is to learn to predict which of a designated set of uncertain events will occur following a signal. In the experimental situation used for this type of study in our laboratory, the ready signal which begins each trial is a pattern of lights on a panel. Following the signal, *S* predicts by operating one of a pair of telegraph keys, $A_1$ or $A_2$, which of a pair of "reinforcing" lights, $E_1$ or $E_2$, he expects to follow. Actually $E_1$ and $E_2$ appear in accordance with a predetermined random schedule independently of the nature of the signal pattern and of *S*'s behavior. The main findings predicted successfully by the theory are: (*a*) the exponential form of the learning curve, plotted in terms of proportion of $A_1$ responses per trial block; (*b*) the asymptote of the learning curve, with mean response probability equal to the probability of reinforcement; and (*c*) the inverse relation between rate of learning and variability of the signal pattern.

Now let us see how the theoretical treatment can be extended to situations in which probability of reinforcement does depend on the nature of the signal, i.e., situations involving discrimination learning. The princi-

[1] This research was supported in part by a grant from the National Science Foundation. We wish to acknowledge the contribution of our research assistant, Sidney Hellyer, to the conduct of the experiment and analysis of the data.

pal assumptions that we will be concerned with are, in brief (cf. **1, 4** for further discussion): (*a*) An experimentally reproducible stimulus situation, e.g., the signal pattern in a prediction experiment, determines a population of cues, or more formally, stimulus elements, which is sampled by *S* on each trial. (*b*) A reinforcing event determines whether the response that terminates a trial is compatible or incompatible with the response being learned. In a prediction experiment we assume that reinforcing light $E_1$ evokes a response compatible with that of predicting $E_1$ and $E_2$ evokes a response compatible with that of predicting $E_2$. (*c*) The response that terminates a trial is conditioned to the cues sampled on the trial. (*d*) Probability of a response in the presence of a given stimulus population is directly related to (under the simplifying conditions of the present study, equal to) the proportion of elements conditioned to the response.

To convert the learning situation described above into a discrimination problem we need only use two different signal patterns and arrange experimental contingencies so that probability of reinforcement of a given response depends upon which signal pattern is present. Suppose that the set of lights on the signal panel is divided into two nonoverlapping subsets (call them $S_1$ and $S_2$) which are presented in a random order with $S_1$ being followed by reinforcing event $E_1$ 100% of the time and $S_2$ being followed by $E_1$ only 50% of the time. How should we expect learning to proceed under these conditions?

If there were no stimuli in the situation at the beginning of a trial except the signal lights, then over a series of trials all of the stimulus elements in $S_1$ would become conditioned to response $A_1$, while elements in $S_2$ would be equally likely to become conditioned to either response. Thus the curve of responding in $S_1$ would go

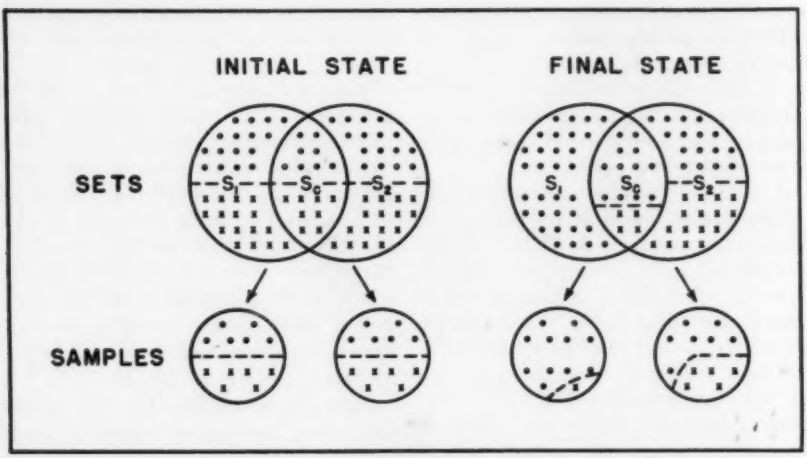


FIG. 1. Schematic representation of discrimination learning. Response $A_1$ is reinforced with probability 1.0 on trials when $S_1$ is presented and with probability .50 when $S_2$ is presented. The large circles represent the stimulus sets to be discriminated, some elements being common to the two sets. Stimulus elements conditioned to response $A_1$ are represented by dots, elements conditioned to $A_2$ by x's. The small circles represent samples of stimulus elements which are drawn on individual $S_1$ and $S_2$ trials.

to 100% $A_1$ responding and the curve in $S_2$ would fluctuate around the 50% level.

It is not quite true, however, that the lights are the only stimuli in the situation. There must also be some background cues and some response-produced stimuli from preceding trials, and these will be common to $S_1$ and $S_2$ trials. Conditioning to the common elements should be expected to proceed as on a random reinforcement schedule; in the present instance, response $A_1$ will be reinforced, on the average, 75% of the time in the presence of the common elements, and therefore the proportion of these elements conditioned to the response should tend to .75 as an asymptote. As illustrated in Fig. 1, *S* will sample some common elements and some elements from $S_1$ or $S_2$ on each trial. Therefore the effect of the common elements will be to draw the probability of an $A_1$ response in $S_1$ somewhat below and the probability in $S_2$ somewhat above the values of 1.0 and .50, respectively, that they would otherwise have.

Under these conditions, effects of stimulus variability should be the same as those found previously (1) in the simple random reinforcement situation with a single stimulus set. The greater the size of the trial sample relative to the size of the total stimulus set (see Fig. 1) the faster will be the predicted rate of learning.

To test the adequacy of this analysis, we have carried out a study of discrimination learning in human *Ss* which differs from previous investigations in three salient respects: (*a*) the simplicity of the experimental conditions, an obvious prerequisite for quantitative analysis; (*b*) the use of partial reinforcement rather than uniform nonreinforcement on the "negative" stimulus; and (*c*) the inclusion of stimulus variability as an experimental parameter.

## Method

*Apparatus.*—The apparatus has been described in detail elsewhere (4). The experimental room was dark except for light coming from the apparatus, and contained four booths and a signal panel. On the signal panel were mounted 12 12-v., .25-amp. light bulbs, evenly spaced around a circle of 9-in. radius. The booths were placed so that all *Ss* would have a clear view of the signal panel at a distance of approximately 7 ft. Within each booth was a pair of telegraph keys, each key directly beneath a reinforcing light. The presentations of the signal and of the reinforcing stimuli were controlled by an automatic programming device and the responses of *Ss* were recorded automatically.

*Subjects.*—The *Ss* were 128 students obtained from beginning courses in psychology during the academic year 1952–53. They were scheduled in subgroups of four for the experimental sessions. Within each part of the experiment, each group of four was assigned randomly to a treatment group, with the restriction that there be an equal number of *Ss* under each treatment.

*Design.*—Four groups of *Ss* were run for 240 trials in the experimental situation described above. For each *S* the 12 lights on the signal panel were divided into two subsets, $S_1$ and $S_2$. For all groups $S_2$ was followed by each reinforcing light with a .50 probability throughout the series. For two of the groups, constituting Part I of the experiment, $S_1$ was always followed by reinforcing light $E_1$ during the first half of the series and always by $E_2$ during the second half. Since we will measure learning in terms of changes in probability of response $A_1$, we will refer to the first half of the $S_1$ trials as conditioning and the second half as extinction. For the other two groups constituting Part II of the experiment,

TABLE 1

Probability of Reinforcement by the $E_1$ Light Following Stimulation from the $S_1$ or $S_2$ Signal Sets*

| Part | Set | Trials 1–120 | Trials 121–240 |
|---|---|---|---|
| I | $S_1$ | 1.0 | 0 |
| | $S_2$ | .5 | .5 |
| II | $S_1$ | 1.0 | 1.0 |
| | $S_2$ | .5 | .5 |

* Design applies to both the Constant stimulus group and the Variable stimulus group.

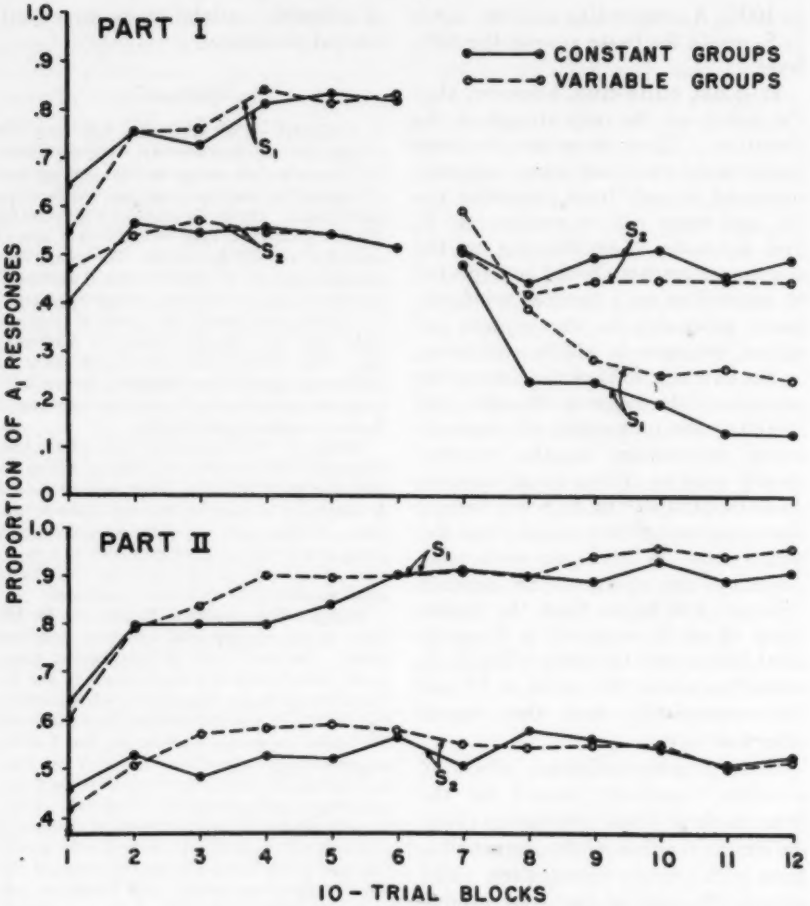


FIG. 2. Obtained data for all groups in terms of mean proportion of $A_1$ responses per block of 10 trials in the presence of stimulus set $S_1$ or $S_2$ as indicated.

$S_1$ was uniformly followed by $E_1$ throughout the entire series.

Part I was the originally planned experiment. After Part I was completed, it was decided to run Part II in order to check on the failure of the conditioning and extinction curves to approach asymptotes of unity or zero, respectively. Although the observed terminal levels of response probability in Part I were in good agreement with predictions from the formal theory, they were nonetheless rather surprising from a common-sense standpoint, and further investigation seemed desirable.

Within each part of the experiment, 32 *Ss* were assigned to the Constant stimulus group and 32 to the Variable stimulus group. For the Constant groups all six of the $S_1$ lights appeared on each $S_1$ trial and all six of the $S_2$ lights on each $S_2$ trial. For the Variable groups, a randomly selected sample of three lights from $S_1$ appeared on any $S_1$ trial and a randomly selected sample of three lights from $S_2$ on any $S_2$ trial.

For each subgroup of four *Ss*, either the six signal lights on the left half of the panel or the six on the right half were designated as $S_1$ and the other six as $S_2$. Random sequences of $S_1$ and $S_2$ trials were generated for the subgroups, with the restrictions that $S_1$ and $S_2$ must each be used 120 times in the total series of 240 trials for each subgroup, and that each sequence drawn for a sub-

group of the Constant group should be used also for a matched subgroup of the Variable group.

For each *S*, one of the reinforcing lights was designated $E_1$ and the other $E_2$. Either $E_1$ or $E_2$ appeared following the signal on each trial. The side of the $E_1$ light was counterbalanced within each subgroup of four *S*s and the side of the $S_1$ set within each treatment group. Conditions of reinforcement obtaining in all parts of the experiment are summarized in Table 1 in terms of the probability of $E_1$ after stimulation by $S_1$ or $S_2$.

*Procedure.*—When *S*s had been seated in the booths, they were read instructions, similar in detail to a set reported elsewhere (**4**), to the effect that they were to respond to the signal pattern on each trial by operating the telegraph key corresponding to the reinforcing light that they expected to follow. Then the recorder was started and the 240 experimental trials were run off in continuous sequence. Temporal relations within the series were as follows: signal duration, 2 sec.; interval from cessation of signal to onset of reinforcing light, 1 sec.; duration of reinforcing light, .8 sec.; intertrial interval, .4 sec.

## Results and Discussion

In Fig. 2 are presented empirical curves for all groups, plotted in terms of mean proportion of $A_1$ responses (i.e., depressions of the key below reinforcing light $E_1$) per block of 10 trials in the presence of either stimulus. Over-all trends seem generally in accord with the assumption that discrimination learning in this situation is a simple resultant of the effects of reinforcement and nonreinforcement. It will be noted that curves of responding under uniform reinforcement or nonreinforcement in $S_1$ and curves of responding under partial reinforcement in $S_2$ are similar in most respects to the acquisition and extinction curves reported by previous investigators (**5, 6, 8**) who have studied simple, nondiscriminative learning under similar reinforcement schedules.

Considering the Constant vs. Variable comparison, the rate of conditioning is slightly but insignificantly faster for the Constant group in both parts of the experiment, while rate of extinction in Part I shows a large and significant difference in favor of the Constant group. Analyses of variance using the variance estimate from within-sequence subgroups as the error term show no differences significant at the 5% level during conditioning; during extinction, frequency of $A_1$ responding during the first 20 trials is significant ($F$ of 6.43, with 1, 48 *df*), while differences during the latter half of extinction are not significant ($F$ of 3.96, with 1, 48 *df*). Response frequencies in $S_2$ do not differ significantly for the Constant and Variable groups in either part of the experiment.

As anticipated on the assumption of common stimulus elements, curves of responding in $S_1$ level off somewhat below 1.0 during conditioning and above zero during extinction, while curves in $S_2$ run somewhat above .5 during conditioning and somewhat below during extinction.

For each of the groups in Part I considered separately, rates of conditioning and extinction are approximately equal. The very rapid extinction following 100% reinforcement found uniformly by previous investigators (**5, 6, 8, 9**) does not appear; possibly the procedure of interspersing the $S_1$ trials with the partially reinforced trials in $S_2$ has produced this result by reducing both the homogeneity of the stimulating situation and the opportunities for effective verbalization that usually characterize 100% series with human *S*s.

The fact that the curves of responding in $S_2$ start out below .5 in all cases was not anticipated on theoretical grounds. It is possible that this effect is a manifestation of the same initial "alternation tendency" that has been observed in two-choice situations with random reinforcement (**4, 7**).

In order to facilitate detailed comparisons of the data with predictions

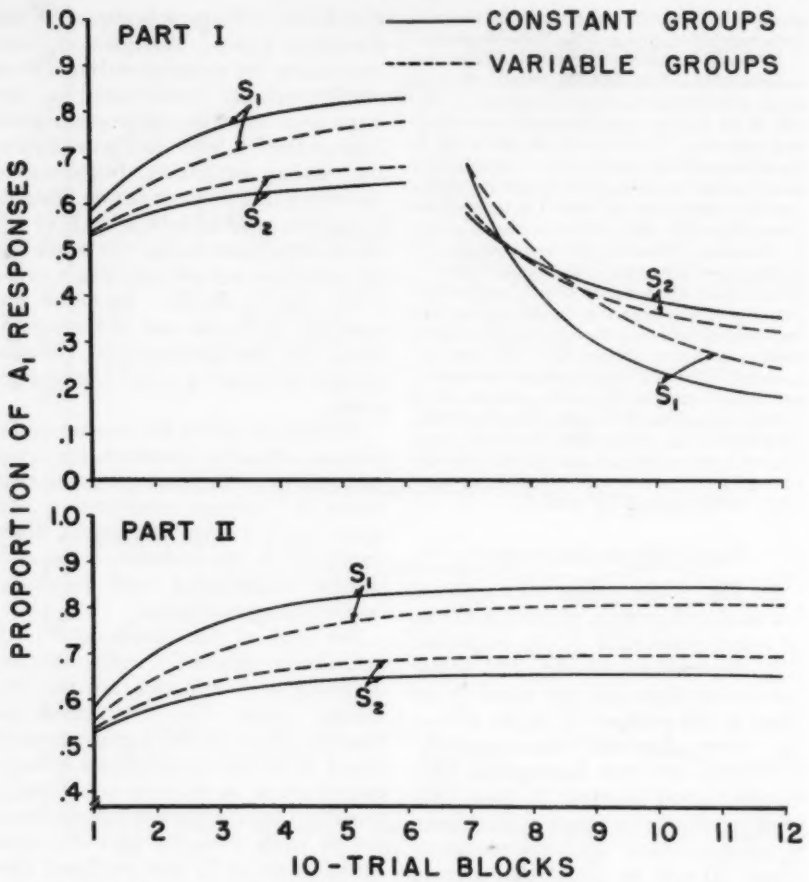


FIG. 3. Predicted curves of discrimination learning in terms of proportion of $A_1$ responses per block of 10 trials in the presence of stimulus set $S_1$ or $S_2$ as indicated.

from the statistical model, the theoretical curves shown in Fig. 3 have been computed from a mathematical formulation of the model schematized in Fig. 1. The derivations are too lengthy to be included here, but will be made available elsewhere.[2]

[2] An article entitled "A model for stimulus variables in discrimination learning" by W. K. Estes and C. J. Burke is in preparation. The mathematical methods needed for the derivations can be found in the recent treatise on stochastic models by Bush and Mosteller (2).

Since the values of the free parameters in the curves of Fig. 3 have been taken from the data of a preceding experiment on simple random reinforcement (1), certain absolute predictions can be considered as well as the relative predictions discussed above. We shall confine our attention to the curves in $S_1$, which are sufficiently orderly to be compared in some detail with the corresponding theoretical curves. Comparing Fig. 2 and 3, it will be seen that the slopes and terminal levels of both conditioning and ex-

tinction curves are surprisingly close to expectation, considering that the predictions are entirely a priori and that no adjustments have been made for observed initial levels. It is the disparities between predicted and observed patterns that are of most interest, however, since these may be expected to provide indications as to the behavioral complications that are associated with the procedural change from simple random reinforcement to a combination of differential and random reinforcement.

The fact that the observed asymptotes appear to be slightly closer to 1.0 and zero during conditioning and extinction, respectively, than the theoretical asymptotes, suggests that the stimulus sets associated with the signal lights may have a greater weight, relative to the set associated with background and response-produced cues, in the discrimination experiment than in the simple random reinforcement experiment. The presence, although not the amount, of this effect could probably have been anticipated in advance, since trials of a given type, say those on which $S_1$ is used, are spaced out by a longer average intertrial interval in the discrimination experiment, and we would assume that under nearly all circumstances, the relative weight of the common stimulus set should be a decreasing function of intertrial interval.

A second set of disparities which may have a common theoretical interpretation should be mentioned. In the empirical curves for Part II it will be observed that the curves in both $S_1$ and $S_2$ appear to level off by the end of the first 50 trials; then the curves in $S_2$ begin to drift back toward .50, while the curves in $S_1$ drift on upward toward 1.0. In Part I also, the curves in $S_2$ have clearly begun to drop back toward .50 before the end of the conditioning series. These observations, together with the smaller than expected differences in learning rate between Constant and Variable groups during conditioning, would be accounted for if there were a progressive reduction in the set of common elements during the course of the experiment. This reduction might occur if, for example, a set of stimulus elements attributable to the giving of instructions and to initial postural and verbal adjustments to the situation on the part of the *S*s were present on the early trials but tended to drop out during the experiment, leaving the signal lights as the principal source of stimulation on later trials. An independent check on this hypothesis will, of course, have to wait upon further experimentation.

In conclusion, it appears that the principal trends in the data of this two-stimulus learning experiment are predictable from the theory developed in connection with simpler experiments. It seems clear, however, that further simplification of the two-stimulus situation, including adequate spacing of trials and minimization of background cues, will be necessary before a reasonably full quantitative account of the course of discrimination learning will be possible.

## Summary

Human *S*s learned a successive discrimination between two sets of signal stimuli. The task was to predict which of a pair of "reinforcing" lights would appear following the signal on each trial. Uniform reinforcement (conditioning phase) or nonreinforcement (extinction phase) was given in the presence of one stimulus set and 50% random reinforcement in the presence of the other. Variability of the signal pattern was a second independent variable.

Curves of responding in the presence of the two stimulus sets taken separately were generally similar to curves reported by previous investigators for learning under similar conditions of reinforcement in nondiscriminative situations. Effects of stimulus variability were insignificant during conditioning but large and significant during extinction, with the more constant stimulus yielding the faster extinction.

An attempt was made to predict the detailed results of this study by means of a statistical model developed in connection with earlier studies of simple learning under random reinforcement. Correspondences of theory and data, although by no means perfect, tended to support the view that discrimination learning in this situation is a simple resultant of effects of reinforcement and nonreinforcement.

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# SIMULTANEOUS BRIGHTNESS INDUCTION AS A FUNCTION OF INDUCING- AND TEST-FIELD LUMINANCES

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By "simultaneous brightness induction" is meant here the effect on the apparent brightness of a test field produced by a second field (the inducing field) presented somewhere in the neighborhood of the test field. This effect may be either an enhancement or a depression of the apparent brightness of the test field. In the previous literature the enhancement has been referred to by a number of terms including "spreading effect" and "assimilation." The depression of the test-field brightness by the inducing field is usually called "simultaneous brightness contrast."

The earliest extensive investigation of brightness induction is that of Hess and Pretori (**11**). They investigated the induction effect as a function of test- and inducing-field luminances for a 1° × 1° square test field completely surrounded by a 10° × 10° inducing field. Their measurements were based on the monocular brightness matches made by *S* between the test field and a comparison field of the same dimensions. This comparison field was also surrounded by a 10° × 10° inducing field. Thus altogether the stimulus pattern included *four* fields of different luminance. As has been pointed out by Diamond (**3**), an unambiguous interpretation of Hess and Pretori's results is almost impossible because of the many possible interactions among the four fields.

The difficulties present in Hess and Pretori's investigation have been avoided in more recent investigations by use of the binocular matching method (**3, 5, 15, 19**). With this method the test and inducing fields are presented to one eye only, and the comparison field (usually of the same shape and size as the test field) is presented to the other eye only. These monocular fields are made to fall upon noncorresponding points, so that they appear side by side to *S*. The *S* is then required to match the apparent brightness of the test and comparison fields. Interaction between the two eyes is negligible under these conditions (**3, 22**) so that a relatively pure measure of the induction effect is obtained.

With this method, induction has been studied as a function of test- and inducing-field luminances by Fry and Alpern (**5**) and Diamond (**3**), and as a function of degree of separation between test and inducing fields by Fry and Alpern (**5**) and Leibowitz, Mote, and Thurlow (**15**). In Fry and Alpern's investigation the test field was a 2.5° × .5° rectangle centered between two inducing fields of the same size and shape. In Diamond's investigation the test and inducing fields were adjacent squares 33′ × 33′, and in the investigation by Leibowitz, Mote, and Thurlow the test and inducing fields were 30′ × 30′ squares.

These investigations agree in showing little if any effect upon the apparent brightness of the test field by inducing-field luminances *less* than the test-field luminance, and a depression of the test-field brightness by inducing-field luminances *greater* than the test-field luminance.

## METHOD

In the experiments reported here the effect of varying the luminances of the test and inducing fields was studied for a disc-shaped test field completely surrounded by a contiguous annular inducing field. The method used was binocular matching. The test and inducing fields were presented to *S*'s right eye; a comparison field of the same shape and size as the test field was presented to *S*'s left eye.

The induction effect may be measured in two ways.

*Method* 1.—With constant luminance of the test field, *S* matches the apparent brightness of the test and comparison fields by varying the luminance of the comparison field. At different luminance levels of the inducing field, changes in the apparent brightness of the test field are reflected in changes in *S*'s luminance settings of the matched comparison field.

*Method 2.*—With constant luminance of the comparison field, *S* matches the brightnesses of the comparison and test fields either by adjusting the luminance of the test field at each of several luminance levels of the inducing field, or by adjusting the luminance of the inducing field at each of several luminance levels of the test field. Either of these variations yields a set of paired test- and inducing-field luminance values for which the test field has the same apparent brightness as the constant comparison field.

Method 1 was used in Exp. 1 to study changes in the apparent brightness of the test field as a function of inducing-field luminance at several different luminance levels of the test field. The inducing-field luminances used in this experiment ranged from approximately threshold to values slightly larger than the test-field luminance. For reasons to be given later, the effect of inducing-field luminances appreciably in excess of the test-field luminance could not be measured in this experiment. Method 2 was used in Exp. 2. In this experiment the range of inducing-field luminances used was extended to include values much larger than the test-field luminance.

*Apparatus.*—The stimulus pattern seen by *S* is shown in Fig. 1. The comparison field *C*, the inducing field $I_2$ (used only in Exp. 2), and the fixation point $F_2$ are presented to *S*'s left eye only. The test field *T*, the inducing field $I_1$, and the fixation point $F_1$ are presented to *S*'s right eye only. The *S* is required to fuse the two fixation points so that in the binocular view he sees a single fixation point to either side of which

FIG. 1. The comparison field *C*, the inducing field $I_2$, and the fixation point $F_2$ are presented to *S*'s left eye only; the test field *T*, the inducing field $I_1$, and the fixation point $F_1$ are presented to *S*'s right eye only.

appears a disc, either one of which may be surrounded by an annulus.

The fixation points subtend an angle of 4′; their luminance was not varied in the course of the experiments. The angular distance between the fixation point $F_1$ and the center of the test field is equal to that between $F_2$ and the center of the comparison field and is 52′. The test and comparison fields each subtend an angle of 28′. The angular distance between the center of the test or comparison field and the outer border of the annulus is 27.5′.

The essential features of the apparatus are shown in Fig. 2. *A* is a large aluminum screen containing four circular apertures, *l*, $F_2$, $F_1$, and *r*. $F_2$ and $F_1$ are the fixation points, illuminated from behind by a flashlight bulb enclosed in a metal housing. The outer borders of the two annuli are formed by the edges of apertures *l* and *r*. $I_1$ and *T* are two diffusing plates, placed 38 cm. and 80 cm., respectively, behind screen *A*. Both plates are mounted with their horizontal axes parallel to the horizontal axis of screen *A*, and the orthogonal axes inclined 45° to the vertical axis of screen *A*. *T* is a solid plate while $I_1$ has in its center an aperture of such shape that its projection upon screen *A* forms a circle concentric with the circular aperture *r*. Two more diffusing plates, not shown in Fig. 2, are arranged in identical fashion behind aperture *l*. The dif-

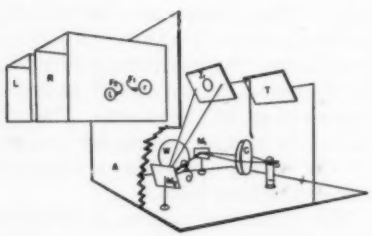


FIG. 2. Simplified diagram of the apparatus used to produce the stimulus pattern shown in Fig. 1.

fusing plates are made of brass which was painted flat white, then coated thickly with barium sulfate.

All four diffusing plates are illuminated by the same light source, a 108-w., 6-v. spiral tungsten filament projection lamp (GE 18A-T10). The illumination on each plate can be varied independently by a neutral density wedge in tandem with a neutral density filter. Figure 2 shows the optical arrangement for plate $I_1$ only. An identical arrangement is used for the other plates. Four sets of condensing lenses are placed around the source. One such set $C$ is shown in Fig. 2. After passing through the condensing lenses $C$, the light is reflected by the first surface mirror $M_1$. Next it passes through the neutral density wedge $W$, then the objective lens $O$, then it is reflected to the diffusing plate by the first surface mirror $M_2$. An image of the filament is formed in the plane of wedge $W$. The objective lens $O$ also is approximately in the plane of this image. An image of the second condensing lens, evenly filled with light, is formed on the diffusing plate. The optical arrangement also included a holder for neutral density filters. This holder, not shown in Fig. 2, was placed immediately next to the objective lens, between this lens and the mirror $M_2$.

$L$ and $R$ are two light-tight tunnels, 2.5 m. long, leading to a light-tight booth in which $S$ observes. The $S$'s head is fixed by a biting-board so that his left eye sees the pattern at the end of tunnel $L$, his right eye the pattern at the end of tunnel $R$. The distance from the screen $A$ to the eyes of $S$ is 2.53 m. All observations were made with 2.75-mm. artificial pupils.

Within easy reach of $S$ is placed a knob to which one end of a long flexible shaft is attached. The other end of the flexible shaft can be attached to the driving mechanism of any one of the wedges so that $S$ may vary the luminance of any of the four fields.

All calibrations were made with a Macbeth illuminometer.

## Experiment 1

*Procedure.*—In this experiment, the variation of the apparent brightness of the test field with the luminance of the annular inducing field was studied at seven different luminances of the test field. The method of adjustment (7) was used throughout. The stimulus pattern used contained all the elements shown in Fig. 1 except the inducing field $I_2$. The $S$ was given control over the luminance of the comparison field. He was instructed to vary this luminance until the comparison field and test field were matched for brightness, taking care to "bracket" the equality point. In a given experimental session the luminance of the test field was held constant at one of seven different values ranging from −1.45 to 1.55 log mL., and matches were made for from 7 to 12 different luminance levels of the inducing field.

Prior to each session $S$s were dark adapted for 20 min. The $S$ began each session by making eight matches between the test and comparison fields in the absence of the inducing field. The inducing field was then introduced at a level near threshold, and eight more matches were made. This procedure was repeated for a series of progressively higher luminance values of the inducing field.

The mean of the first eight matches, made in the absence of the inducing field, was accepted as a measure of the luminance of the comparison field. Thus the results are independent of differences in the response of the two eyes. Such differences were found to vary from $S$ to $S$ and from session to session for the same $S$.

Each $S$ had at least 4 hrs. practice, spread over several days, before beginning the experiment. Two $S$s were used, both experienced in visual experimentation. As a check one or more functions were determined on a number of $S$s wholly inexperienced in visual experimentation. Their results did not differ in any consistent manner from those of the two experienced $S$s and are not reported.

*Results.*—The results of Exp. 1 are shown in Fig. 3.[1] The log of the luminance of the comparison field required to make it match the test field in apparent brightness is plotted against the log luminance of the inducing field. Seven different curves are shown, one for each of the seven luminance levels of the test field used. For Subject FR the comparison field values represent the mean log luminance of 8 settings; for Subject EGH, the mean log luminance of 16 settings, obtained in two groups of 8 each on two different days. Curves were fitted to the points visually.

The curves show that the apparent brightness of the test field is raised somewhat by inducing fields of luminance considerably below the test

[1] The results are also given in a table deposited with the American Documentation Institute. Order Document No. 4548, $1.25 for microfilm, or $1.25 for photocopies.

field. As the luminance of the inducing field approaches equality with that of the test field, the apparent brightness of the test field decreases. It decreases progressively more rapidly as the luminance of the inducing field equals and then exceeds that of the test field.

The initial rise in apparent brightness is slight but it appears consistently in every curve for both *Ss*.

## Experiment 2

As the luminance of the inducing field becomes larger than that of the test field a point is soon reached at which a match is no longer possible. At and beyond this point the comparison field appears brighter than the test field for any suprathreshold luminance of the comparison field. This point is reached when the test field has not yet attained its threshold value, i.e., when the test field can be made to appear still darker by a further increase in the luminance of the annulus. For this reason, with the stimulus arrangement used in Exp. 1, measurements could not be made when the luminance of the inducing field exceeded that of the test field by more than about .1 log unit. The principal purpose of Exp. 2 was to study induction over a range including inducing-field luminances greatly in excess of test-field luminances. To make measurements at high (relative) inducing-field luminances, it was necessary to extend downward the range of possible apparent brightnesses of the comparison field by surrounding this field with an illuminated annulus. This was done in one half the sessions of Exp. 2. In the remainder of the sessions the comparison field was presented against a completely dark background, as before. Method 2 was used rather than Method 1 so that the data obtained with these two stimulus arrangements might be plotted within a single coordinate system in the form of equal brightness curves.

*Procedure.*—Six curves were obtained, one in each of six different experimental sessions. In three of these sessions the comparison field was presented without the inducing field $I_2$ (see Fig. 1). Throughout each of these sessions the luminance of the comparison field was held constant at one of four levels ranging from −1.20 to 1.65

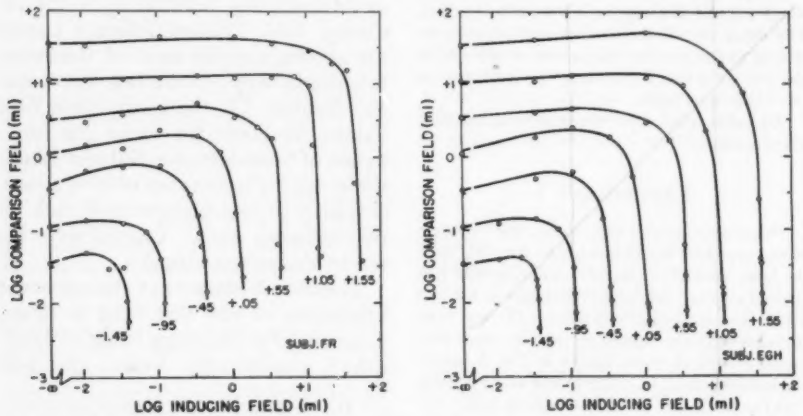


Fig. 3. The comparison-field luminance required for an apparent brightness match between the comparison field and the test field as a function of the luminance of inducing field $I_1$, for various test-field luminances. The parameters on the curves are the test-field luminances in log milliLamberts.

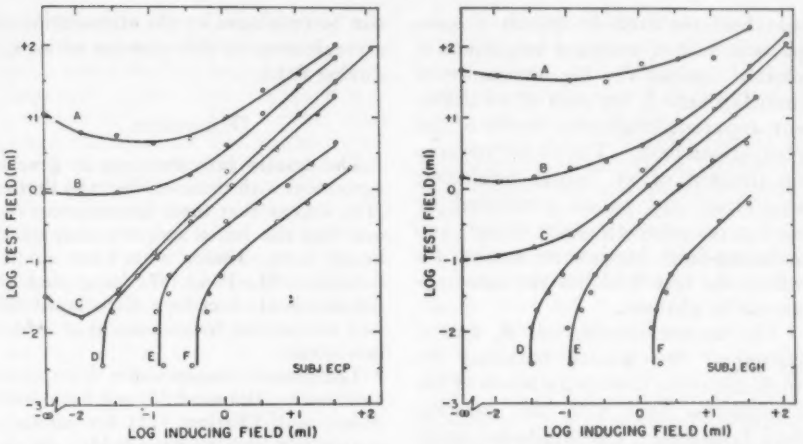


FIG. 4. The test-field luminance for which the apparent brightness of the test field equals that of a constant comparison field as a function of the luminance of inducing field $I_1$, for six apparent-brightness levels of the comparison field. For curves *A*, *B*, and *C*, the comparison-field luminance is the ordinate corresponding to log inducing-field luminance $-\infty$; for curves *D*, *E*, and *F*, the ordinate corresponding to log inducing-field luminance 1.05.

log mL. The *S* matched the apparent brightness of the test and comparison fields by varying the luminance of the test field.

The luminances of all fields were measured with a Macbeth illuminometer by *E*, thus the tabulated results of the present experiment are not corrected for differences in the response of the two eyes. In all other respects the procedure used in these three sessions was the same as that used in Exp. 1.

In the three remaining sessions the stimulus pattern contained, in addition to the elements described above, the inducing field $I_2$ surrounding the comparison field. Throughout all three of these sessions the luminance of the inducing field $I_2$ was held constant at 1.05 log mL. The luminance of the comparison field was held constant throughout each session at one of four levels varying from $-.45$ to .85 log mL. The *S* matched the apparent brightness of the test and comparison fields by varying the luminance of the inducing field $I_1$, which surrounds the test field, rather than the luminance of the test field itself.[2]

The luminance of the comparison field was considerably below that of its inducing field ($I_2$) in each of these sessions. Under these conditions the comparison field always had an apparent brightness *lower* than the lowest apparent brightness that a comparison field which is not surrounded by an inducing field can show.

Further departures from the previous procedure are as follows. At the beginning of each session the test field had a luminance near or below threshold. The *S* adjusted the inducing field $I_1$ until the test and comparison fields were matched in brightness. As before, eight matches were made and the procedure was then repeated for a series of progressively higher luminance values of the test field.

Two *S*s were used. One of these had served as *S* in Exp. 1. The other *S* had had no previous experience in visual experiments of this sort but had had 4 hrs. of practice before beginning the experiment.

*Results.*—The results of Exp. 2 are shown in Fig. 4. The mean log luminance of the test field (based on 8

[2] It was found in preliminary experiments that the functions obtained with this procedure differ in no significant way from those obtained when *S* makes matches by varying the luminance of the test field. However, if *S* varies the luminance of the test field, the following difficulty arises. When the luminance of the inducing field surrounding the test field ($I_1$) is quite low, the test field may have to have a luminance very near threshold to make it match the comparison field; *S* is unable to make the test field appear darker than the comparison field and thus cannot bracket the equality point. This difficulty is avoided by the procedure followed.

matches) required to match a comparison field of constant brightness is plotted against the log luminance of inducing field $I_1$ for each of six different apparent brightness levels of the comparison field. The six curves may be thought of as "equal brightness contours:" the points connected by each curve represent pairs of test- and inducing-field luminance values for which the test field has the same apparent brightness.

The curves labelled *A*, *B*, and *C* represent the results obtained for three different luminance levels of the comparison field with the inducing field $I_2$ absent. The luminance levels of the comparison fields (corrected for differences in the response of the two eyes) are given by the ordinate corresponding to log inducing-field luminance $-\infty$. These results do not differ in any significant respect from those of Exp. 1. The initial rise in the curves of Fig. 3 shows as an initial dip in the representation used in Fig. 4, though this is not present in all the curves shown here. As in Exp. 1, depression of the visual effect of the test field occurs when the inducing-field luminance is still below the test-field luminance.

The curves labelled *D*, *E*, and *F* represent the results obtained for three different luminance levels of the comparison field when it was surrounded by an inducing field of luminance 1.05 log mL. The corrected luminance levels of the comparison field are the ordinates corresponding to log inducing-field luminance 1.05. One of the most marked differences between these curves and curves *A*, *B*, and *C* is that the former do not approach the y-axis even as the test-field luminance goes to threshold. This reflects the fact, mentioned above, that the apparent brightness levels of the comparison field under these conditions are below any that can be produced by the stimulation of a single area in the absence of an inducing field.

## Discussion

The results presented are in general agreement with those of Hess and Pretori (**11**), except that these investigators did not find the initial enhancement effect found here. Under somewhat similar conditions MacLeod (**17**) found such an enhancement effect for a disc-shaped test field surrounded by an annulus of graded luminance.

The present results differ from those obtained by Diamond (**3**) and Leibowitz, Mote, and Thurlow (**15**) for adjacent square test and inducing fields. In the present experiments, inducing fields of luminance less than that of the test field produced first an enhancement and then a depression of the visual effect of the test field; Diamond found virtually no effect for comparable luminance conditions (the data of Leibowitz, Mote, and Thurlow show what may be a slight enhancement effect). For inducing fields of luminance greater than that of the test field the depression of the visual effect of the test field is found to be much more rapid in the present experiments than in the experiments just cited.

One of the factors to be considered in the interpretation of the results is the state of adaptation of the two eyes. Though *S*s were instructed to fixate, the eyes cannot be considered to be stationary. It has been shown in several studies that eye movements of varying extent and frequency occur during attempted fixation (cf. **18**). Because of the constant occurrence of eye movements and the small size of the test and comparison fields, the areas stimulated when the test and comparison fields are presented without an inducing field are probably adapted to a luminance level slightly below the luminance level of these fields. When either of these fields is surrounded by an inducing field, the stimulated area is adapted to a level which depends on the luminance and area of both the inducing field and the test or comparison field. In Exp. 1 and

the first part of Exp. 2, only the test field is surrounded by an inducing field, so the eye to which the test field is presented is adapted to a higher luminance level than is the other eye. This factor alone should make the test field appear darker than a comparison field of equal luminance (cf. **2**).

Retinal adaptation is thus probably responsible for part of the depressive or "inhibitory" effect obtained. The inhibitory effect found for inducing-field luminances less than the test-field luminance might be wholly the result of such adaptation, but that the effect found when the inducing-field luminance exceeds the test-field luminance is wholly due to this is very doubtful in view of the work of Schouten and Ornstein (**19**) who found that such effects can be obtained with exposures of the inducing field briefer than 1/10 sec. These exposures are too short to allow any considerable displacement of the retinal image by eye movements. More likely, then, the inhibitory effect is due in part to some physiological interaction within the visual system.

It might be supposed that the *enhancement* effect is due simply to the addition of stray light from the inducing field to the test field. Two objections may be raised to this: (*a*) Under similar conditions enhancement effects are also found for differential sensitivity (**1, 4, 6**) and acuity (**16**). Since a veil of stray light decreases the contrast between the object and its background, it should impair discrimination rather than improve it. (*b*) The enhancement effect seems too large to be accounted for in this fashion. Even for those curves of Fig. 3 that show the smallest rise, the enhancement near its maximal value is larger than would be expected even on the clearly erroneous assumption that *all* the inducing-field luminance is added to the test-field luminance. This point cannot be regarded as conclusively established until the absolute magnitude of the enhancement effect has been measured with greater precision than was done here. Nonetheless, it seems more probable that the enhancement effect also reflects some interaction effect within the visual system. Both facilitation and inhibition are known to occur within the visual system but the present experiments provide no way of choosing among many possible mechansims.

The data obtained in the present experiments may be useful in interpreting the results of experiments on brightness constancy. In many such experiments the apparent brightness of a surface presented in front of a reflecting background is studied as a function of the illumination level (cf. **9, 13, 21**). The test surface and its background usually receive the same illumination, so that changes in illumination level leave the log luminance difference between the test surface and the background unchanged. Many workers have expressed the view that one of the primary reasons for the brightness constancy obtained under these conditions is the fact that the brightness of the test surface is determined almost wholly by this log luminance difference between it and the background (**8, 12, 14, 20**). The general view that brightness constancy is largely the result of brightness contrast was first expressed by Hering (**10**).

To compare the present results to those obtained in constancy experiments the representation used in Fig. 4 is most convenient. To yield a prediction of perfect constancy the equal brightness contours would have to be straight lines of slope 1. The near-linear portions of these functions do have approximately this slope. Under most conditions, of course, complete constancy is not found. The direction of departures from complete constancy found as a function of illumination level and relative reflectance of the test field and the background is generally that implied by the curvature of the functions of Fig. 4 (cf. **9**).

A more detailed interpretation of the results of brightness constancy experiments in terms of brightness induction must await the study of such variables as the duration of exposure of test and inducing fields, area of test and inducing fields, and the manner in which several inducing fields may act upon a single test field. Research on some of these problems is now under way.

## Summary

By means of a binocular matching method, simultaneous brightness induction was studied as a function of test- and inducing-field luminances. The test field was disc shaped and was surrounded by a contiguous annular inducing field.

In the two experiments *S* made brightness matches between a test field and a comparison field of the same size and shape. In Exp. 1 the comparison field was presented against a completely dark background and *S* varied the luminance of the comparison field to make the match. With this procedure the effect of inducing fields whose luminance exceeds that of the test field by more than approximately .1 log unit cannot be measured; for inducing fields of greater luminance the test field appears darker than the comparison field for any suprathreshold luminance of the latter.

The effect of inducing fields of luminance greatly in excess of the test-field luminance was measured when the comparison field was made darker by surrounding it with an illuminated annulus. This was done in Exp. 2. The procedure of Exp. 2 differed from that of Exp. 1 in that *S* made the matches by varying either the luminance of the test field or of the inducing field surrounding the test field.

It was found that inducing fields of luminance much lower than the test-field luminance slightly *enhance* the visual effect of the test field. Inducing fields of luminance almost as great or greater than the test-field luminance *depress* the visual effect of the test field.

Possible theoretical interpretations of the results and the application of the results to the analysis of brightness constancy are discussed.


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# THE EFFECT OF PRIOR TRAINING WITH A SCALE OF DISTANCE ON ABSOLUTE AND RELATIVE JUDGMENTS OF DISTANCE OVER GROUND [1]

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The present experiments are part of a program of research concerned with the effect of training on judgments of distance viewed over a ground surface out-of-doors. A previous experiment (**3**) demonstrated that training by a correction method improved absolute estimation of distance in yards, even when none of the stretches of distance presented for training or test were duplicated. Since association of a particular stretch of ground with a particular yard value was prevented, it was hypothesized that *S* had achieved a better correspondence between a conceptual scale of yards and stimulation provided by the ground as it receded to the target. The conceptual scale would be in correspondence with gradients of stimulation provided by a ground surface but not with those of any *particular* ground surface.

In the experiments to be described, each *S* of the experimental group was "taught" a scale of distance (cf. **3**, p. 481) on one judging ground and then was required to judge distances on a different field. The first experiment sought to determine the effect of this training on the absolute estimation of distance, in yards, to unfamiliar targets at varying distances. Would the preliminary training transfer, by comparison with a control group, to absolute judgments on a new field with new targets?

The second experiment was concerned with the effect of this training on relative judgments of distance. If the experimental group were to show reduced DL's (greater precision) than the control group, it could be concluded that perceptions of relative distance become better differentiated with practice.

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## Experiment I

### *Method*

*Training procedure.*—The training was carried out in a large grassy quadrangle approximately 350 yd. long. Trees and buildings were visible at the sides, and several walks cut across the terrain, but *S* had an uninterrupted view of its entire length. A 300-yd. flat stretch was chosen for the scale, and a large marker labeled 300 was set up. The boundaries or ends of the scale were thus provided by *S*'s own station point and the 300-yd. marker. The only raised object along this stretch was a fire hydrant which stood exactly 10 yd. in front of *S*'s station point and was used to mark off a *unit* for his scale. The unit and the end were thus defined for *S* at the beginning of training.

The learning of the *intervals* within this scale was accomplished by having *S* divide the 300-yd. stretch into progressively smaller fractions. A moving marker (a bicycle equipped with white metal flaps on the front axle) was started at one end of the 300-yd. stretch and kept moving until *S* thought it had reached the appropriate division point. The *E*, who stood beside *S*, then signaled the bicycle rider to stop by blowing a policeman's

whistle. The rider dismounted at this point and walked to the correct division point, where he set up a marker, painted white and labeled with the number of yards distant from *S*. This procedure enabled *S* to see the direction and approximate extent of his error. The rider then remounted the bicycle and began the procedure of the next fractionation judgment.

The total stretch was first bisected, and then further subdivided into halves or thirds until markers had been placed at 25-yd. intervals along the scale. (An exception was made at 275 yd. since the interval was very difficult to detect at this distance.) Thus practice consisted of 10 *corrected* fractionation judgments, ending with a scale marked at 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, and 300 yd. For any given *S* the bicycle always approached, or always withdrew, for all the judgments, but the direction of movement was varied for different *S*s. The entire procedure required about 20 min.

*Testing procedure.*—The *S*s who took part in the training just described constituted the experimental group. At the end of training, each *S* was conveyed by automobile to a large athletic field (488 × 132 yd.). Here he was asked to make absolute judgments in yards of the distance of targets spaced from 52 to 395 yd. away from his station point. The procedure for obtaining these judgments, the targets, and their layout on the field was exactly as described by Gibson and Bergman (**3**). Eighteen judgments, each of a different distance, were made. No anchor point was defined for *S* on this field. He was not told how long it was, or the distance to any point on it. The field resembled the training arae in having a flat mowed grass surface, but there was no resemblance in other scenery or in the targets. The targets were constructed of metal plates mounted on stakes. The plates were painted white, yellow, or black so that each target was unique and could be identified. No target intercepted another as *S* viewed them. The judgments asked for were identical with the pre- and posttest of the earlier experiment (**3**), and were made from the same station point.

In addition to these 18 judgments, *S* was asked to estimate the distance to four "landmarks" visible from his station point. The landmarks were a tall chimney of the University heating plant, a tower of another University building, a low athletic building, and a house on a low hill adjacent to the campus. Trees and other objects intervened beyond the limits of the field, so there was not a continuous stretch of ground between *S* and these structures.

Procedure for the control group was identical with that for the experimental group, except that there was no preliminary training. There were 35 *S*s in each group, all airmen in basic training from Sampson Air Force Base.

## *Results*

*Analysis by subjects.*—Before statistical treatment, all the estimates were converted into three-place logarithms. The individual error scores for the experimental group and the control group were compared by obtaining a constant error of estimation for each *S*. These errors were then ranked, regardless of sign, and the two groups compared by Wilcoxon's nonparametric test for paired replicates (**9**). The control group's error exceeded that of the experimental group at the .0002 level of confidence, indicating that the training effectively carried over. This finding verifies the expectation that training with the distance scale effects an improvement in absolute estimations of the distance to unfamiliar targets on an unfamiliar field.

*Analysis by target distance.*—Table

TABLE I

GEOMETRIC MEAN ESTIMATES IN YARDS AND PERCENTAGE *SD** FOR TARGETS AT VARYING DISTANCES

| True Distance of Target | Group E ($N$ = 35) | | Group C ($N$ = 35) | |
|---|---|---|---|---|
| | Estimated Distance (Yards) | *SD* (%) | Estimated Distance (Yards) | *SD* (%) |
| 52 | 63.6 | 52 | 47.3 | 113 |
| 68 | 71.4 | 53 | 60.5 | 87 |
| 107 | 107.7 | 42 | 86.8 | 92 |
| 126 | 115.4 | 45 | 102.2 | 82 |
| 139 | 148.7 | 46 | 105.6 | 77 |
| 154 | 181.4 | 42 | 124.6 | 100 |
| 166 | 163.0 | 43 | 131.0 | 82 |
| 188 | 188.6 | 31 | 151.2 | 101 |
| 219 | 190.7 | 38 | 171.9 | 75 |
| 232 | 238.5 | 31 | 234.8 | 139 |
| 252 | 255.0 | 27 | 218.5 | 90 |
| 274 | 267.2 | 29 | 240.3 | 105 |
| 287 | 315.4 | 23 | 348.4 | 125 |
| 304 | 280.0 | 30 | 274.2 | 113 |
| 328 | 311.3 | 36 | 356.5 | 114 |
| 342 | 309.2 | 25 | 288.3 | 101 |
| 369 | 360.9 | 22 | 400.0 | 102 |
| 395 | 333.8 | 24 | 353.5 | 105 |

* The *SD*, in logs, is converted into a ratio by finding its antilogarithm; this, times the geometric mean, gives a score 1 *SD* above the mean; and divided into it, 1 below. Values in the table have been converted to percentages by subtracting 1 and multiplying by 100.

1 gives the geometric mean estimate in yards and the percentage *SD* for each of the 18 target distances. The mean estimates of the experimental group are more accurate than those of the control group for 15 of the 18 target distances. By a sign test, this difference is significant at better than the .01 level, indicating again that training influenced favorably the yard estimates made on the new field. The *SD* also is decreased markedly as a result of training. The percentage *SD*'s are very large for the control group, and show no tendency to vary with distance. Not only are they reduced for the experimental group, they also show a tendency to grow smaller as distance increases.

The function relating true distance to estimated distance is plotted in Fig. 1. The relationship is linear, as previous studies have shown (**6, 3**); perceived distance increases as real distance does. But it will be noted that the control group tended to underestimate; 14 of the 18 targets yielded negative CE's. The experimental group, on the other hand, underestimated for 9 of the 18 targets and overestimated for the other 9. The five most distant targets are underestimated. They are all beyond 300 yd., the point at which the practice scale ended.

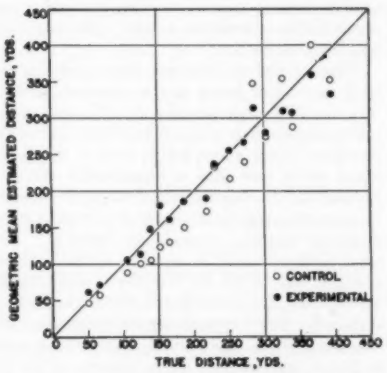


FIG. 1. Geometric mean estimated distance as a function of true distance for the experimental and control group.

TABLE 2

ANALYSIS OF VARIANCE OF ERRORS OF DISTANCE ESTIMATION (IN LOG UNITS)

| Source | *df* | Mean Square | | *F*: C/E* | *p* |
|---|---|---|---|---|---|
| | | Group E | Group C | | |
| Targets | 17 | .0626 | .1091 | 1.74 | >.05 |
| Men | 34 | .1558 | 1.4029 | 9.00 | <.001 |
| Residual | 578 | .0107 | .0169 | 1.579 | <.05 |
| Total | 629 | | | | |

* These comparisons by the *F* test are presented as a matter of interest, although the variances for the two groups are clearly unequal. The principal conclusion is supported by nonparametric tests.

An analysis of variance (Table 2) was performed on the errors of estimation for each group. The component variances are all lower for the experimental group. Between-*S* variance was especially reduced by the pretraining ($p < .001$ when the variances are compared by an *F* test). The residual variances are interpreted as an estimate of individual variable error (**7**). When no judgment is repeated by the individual, the residual variance ("error" term) is the best measure of intraindividual variability, since component variances due to target and individual differences have been removed. Furthermore, any variance caused by experimental error should be equal for the two groups. If, therefore, the control exceeded the experimental group in the residual variance, it can be inferred that intraindividual variability was reduced by training. An *F* test reveals a difference in the expected direction at a little better than the .05 level of confidence.

*Estimation of distance of landmarks.*—For the distance estimates so far considered, there was an uninterrupted grass surface extending from *S*'s station point to the base of the

target. Whether the preliminary training effects any improvement when an uninterrupted flat surface is *not* present can be found in the estimates of the landmarks. The CE's were not consistently smaller for the experimental group (they were greater for this group in two of the four cases). Variance was greater for the control group in three of the four cases, but not significantly. The mean error, regardless of sign, was smaller for the experimental group in all four cases, significantly so ($p < .02$) in three. The evidence for transfer of training to these judgments is therefore equivocal. The absence of a continuous ground stretch is probably responsible for the lack of a clear difference between the two groups.

*Comparison with training by correction.*—In the previous experiment (3) in which *S*s were trained by a correction procedure, training and test judgments were made on the *same* field. In this experiment *S*s had preliminary training by a scaling method, on a different field. Improvement in the two experiments can be compared by calculating the percentage transfer in each case.[2] For the previous experiment, there was 79% transfer based on constant errors; for the present one, 62%. It seems, then, that training with a scale of distance is nearly as effective as correction of judgments on the very same ground where estimation is tested.

## Experiment II

### *Method*

The *S*s were again divided into two groups, experimental and control, and the experimental group was given preliminary training identical with that given the experimental group in Exp. I. Both the control and experimental groups were then required to make relative judgments for pairs of distances over a ground surface. A single distance was thought of as an imaginary line extending radially away from *S*. The question was, how accurately could *S* compare a given stretch of ground along one radius with another along a different radius.

The *S*s were taken to the same athletic field used in Exp. I for relative judgments. The ground was mowed grass, and the field was empty except for the two targets. These were at the ends of two distance stretches making an angle of 120° with *S*'s station point, so that he had to turn his head to compare the distance to each of them. The wide angle was used so that *S* would actually compare the distance stretches, not merely the up and down location of two targets located on the same radius. The targets were of different shapes. The standard target was a white triangle (altitude 94 cm. and base 90 cm.). The variable taget was a rectangle (91 cm. wide and 183 cm. high). The variable target was moved toward or away from *S* by a man concealed behind it. It ran smoothly on bicycle wheels and always made contact with the ground.

The paths of the two targets formed a V, with *S* at the junction point and the standard and variable located at some point along the arms. There were three distances for the standard target, 50, 100, and 200 yd. (The maximum distance of the path along each arm of the V to the corners of the field was 275 yd.) The field had been surveyed by an engineer and stakes were laid at 1-yd. intervals along these lines. They were driven flush with the ground, so that they were invisible to *S*s. Thin wire was stretched along each line so that the target man could follow a straight course. The wire also was invisible to *S*.

The method of judgment was a combination of a method of limits and a constant method. The variable target starting at a distance either much greater than or much less than that of the standard, made a run which took it up to the equal point and then a considerable distance beyond it. During the run, it stopped 10 times at assigned positions to enable *S* to make a judgment of "farther," "equal," or "nearer." The total path traversed on one run by the variable stimulus was 12 yd. for the 50-yd. standard, 24 for the 100-yd. standard, and 48 for the 200-yd. standard. For a typical run where the standard target was 50 yd., the variable target was started at 57 yd. and stopped for judgments at 55, 53, 52, 51, 50, 49, 48, 47, and 45. A typical run for the 200-yd. standard began at 228 yd. with stops at 220, 212, 208, 204, 200, 196, 192, 188, and 180.

[2] Percentage transfer was calulated by the formula $\frac{\text{Group C} - \text{Group E}}{\text{Group C}} \times 100$. A transfer comparison was made rather than direct comparison of the two experimental groups because of the desirability of comparing each Group E with its own control group.

Approach and withdrawal runs were alternated, and the starting point was always varied. For each standard distance the variable made three approach and three withdrawal runs, so that *S* made 60 judgments for each standard distance. The target man kept in constant touch with *E* by radio,[3] so that judgments and stops were coordinated.

For half the *S*s, the standard stimulus was on the left, and for half on the right. Since the illumination of the targets changed from morning to afternoon, these right-left positions were rotated so as to be equally divided between morning and afternoon. Half of the *S*s began their judgments with the 50-yd. standard distance and half with the 200-yd. standard distance. All 60 judgments for a given standard were completed before going on to the next standard. One practice run (10 judgments) was given to make sure *S* understood the task. A rest period of about 10 min. was given after completing judgments for each standard. The judgments for all three standards required about 2½ hr.

Four *S*s took part in the experiment at one time. Each man recorded his own judgments. Two *E*s were always present and watched constantly to insure that *S* was recording in the right blank. The *S*s faced straight ahead after each judgment, while the variable target was moved. The *E* said "Judge" when the target was in place. The *S* was informed when a new run began, and was told that for each run the direction of movement of the variable target would be the same. He was also told that the starting point would vary for each run, and was asked to be sure to compare the stretch of ground between himself and the two targets before making his judgment.

The four *S*s at each session included two members of the experimental group and two of the control group. They stood behind one another, and positions from front to rear were rotated for the two groups so that any advantage of station point would be equalized. All four men could see the targets easily, however. There were 32 *S*s in each group, all airmen in basic training at Sampson Air Force Base.

## *Results*

*The effect of training on differential sensitivity to distance.*—Two measures of sensitivity were obtained, group psychometric functions and individual DL's. To obtain the group psychometric functions, the percentage of responses of *nearer*, *equal*, and *farther* was plotted as a function of the variable distance. Figure 2 shows the function for the control group at 200 yd., with the variable approaching. This plot is fairly typical of all the conditions, showing the expected distribution of responses. The point of subjective equality in this case was displaced outward from the standard distance, at 204 yd. The approach, or descending series, all gave positive constant errors (variable set farther than standard), while the ascending series gave negative ones (variable nearer).

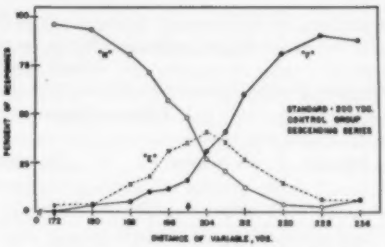


FIG. 2. Group psychometric function for the control group, with the standard set at 200 yd. and variable approaching. The percentage of responses of nearer, equal, and farther is plotted as a function of the variable distance.

The DL's obtained by this method were very similar to those obtained by averaging the DL's of individuals. Individual DL's and the points of subjective equality (PSE) were obtained from each *S*'s responses on the six runs for each standard, according to the method described by Woodworth (**10,** p. 420). Table 3 presents the mean DL's, mean PSE's, and their respective *SD*'s for both control and experimental groups. The limens for the experimental group are slightly lower than those for the control group at all three standard distances, but in no case is the difference significant. A *t* test by paired observations (**2,** p. 105) was made, since this test does not require the assumption of equal variances. None of the *t*'s reaches the .05 level of confidence. It must therefore

[3] Portable radio equipment was kindly loaned by the Cornell Department of Military Training.

TABLE 3

MEAN INDIVIDUAL DL's (IN YARDS) AND PSE's (IN YARDS) AT THREE STANDARD DISTANCES

| Distance | Difference Limens | | | | Point of Subjective Equality | | | |
|---|---|---|---|---|---|---|---|---|
| | Control | | Experimental | | Control | | Experimental | |
| | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* |
| 50 yd. | 1.31 | .59 | 1.24 | .52 | 50.65* | 1.40 | 50.29 | 1.74 |
| 100 yd. | 2.70 | 1.32 | 2.63 | 1.89 | 100.38 | 3.03 | 101.40* | 3.00 |
| 200 yd. | 5.27 | 2.46 | 4.57 | 2.16 | 200.94 | 4.35 | 201.76 | 5.76 |

* These two values differed significantly from the standard distance, showing a small positive CE.

be concluded that training with a scale of distance did not lower differential sensitivity to distance. Limens obtained from the group psychometric functions likewise showed no significant change as a result of the training.

The effect of illumination of the standard and the effect of order (beginning with the 200-yd. standard vs. beginning with the 50-yd. standard) on the DL were calculated separately for experimental and control groups. For illumination, no significant difference in DL was found for either group. That is, it made no difference in the limen whether the standard target was illuminated by direct sunlight or not. Order had no significant effect on the DL for the experimental group, but the control group had significantly lower DL's for two of the three standards (50 yd. and 100 yd.) when *S* began his judgments with the standard at 50 yd., rather than at 200.

*Constant error as a function of training and luminance of standard.*—The PSE did not differ significantly between experimental and control groups. However, there was a small constant error for both groups when ascending and descending trials were averaged (see Table 3). The CE, small as it is, tends to be positive—that is, the variable looked the same distance away as the standard when it was slightly farther.

It might be asked whether bright sunlight shining directly on the standard target would make it appear nearer than when it is not directly illuminated. Many *S*s commented on the apparent difference in brightness depending on the sun's location with respect to the targets. The PSE's were therefore compared for the three standard distances when the standard target was in a position to be directly illuminated and when it was not (when it "looked brighter" or "looked shaded"). None of these differed significantly from the standard distance. In other words, no CE was produced by direct or indirect illumination of the standard target.

*DL as a function of distance.*—As Table 3 shows, the DL in yards increases with distance. The *SD* likewise increases, and is notably large. There was considerable variability in DL's for different individuals. The increment required to produce a change in judgment can be expressed as a percentage of the standard $\left(\frac{\Delta D}{D} \times 100\right)$. For the three standard distances, the mean $DL_f$ is constant at about 2.5%. Over the range of distances used, Weber's Law appears to hold.

*Effect of target separation on SD.*—The judgments of distance obtained in this study required that *S* compare

two stretches of ground receding radially from him, the two radii separated by an angle of 120°. By comparing the present results with those of Teichner, Kobrick, and Wehrkamp (**8**), the effect of increasing angular separation of the standard and variable target can be roughly determined, since their targets were separated by only 3 min. of arc. They used as estimates of linear threshold the *SD* of *S*'s settings around the CE. Comparable measures were computed for our data. For each *S* for each run, we obtained the first variable distance judged "equal" to the standard distance. The *SD* of this distribution is given below for each standard distance (in feet, rather than yards, to conform with the other study):

| *Distance* | *SD* |
|---|---|
| 150 ft. | 10.83 ft. |
| 300 ft. | 21.48 ft. |
| 600 ft. | 40.80 ft. |

These *SD*'s are all higher than those obtained by Teichner *et al.* for the same distances. Here they are about 7% of the standard distance, compared to about 2½% in the other study. Thus judgment of comparative distances over ground gives higher threshold values than does judgment of the coincidence or alignment of two targets at a distance. But reasonably sensitive judgments can clearly be made for comparative distances of two ground stretches.

## Discussion

The results of Exp. I showed clearly that preliminary training with a scale of distance improves absolute estimation of the distance to an unfamiliar target in a new location. The ground surface itself provides a stimulus basis for *S*'s judgment in both training and test fields. The *S* observes along an imaginary line stretching from his feet to the target. Certain optical properties of *any* such line on any level terrain would remain constant in the stimulus array: farther stretches (relative to nearer) are characterized by decreased size and increased density of texture particles, by increased uncrossed disparity, and by increased uncrossed parallactic motion (**4**). Vertical position of a target in the field of view also moves upward with increasing distance. The other classical "cues" for distance are probably irrelevant for the present situation. Familiar size and interposition have been eliminated in the experiment, and the kinesthetic cues are probably of little value for the distances employed.

These variables, we believe, are in a psychophysical correspondence with *impressions of distance along the ground.* The conceptual scale of yards would have to be related to the concomitant gradients of stimulation by means of learning. The relationship, in fact, was vastly improved by the training provided in Exp. I. The *S* can bring with him a scale relationship which will have a beneficial effect on estimations in a new location; even the absence of any objectively confirmed reference point on the new field seemed to be no handicap. And if the yard scale was related, in the training process, to stimulation provided by a continuous stretch of ground, it is not surprising that transfer should be partial or absent when the intervening surface is interrupted by objects or hills or gulleys, as was the case with the "landmark" targets.

The present experiment does not permit us to evaluate the three components included in the scale training. The "unit" of 10 yd., for instance, may have played little role. That the fractionation into 25-yd. intervals had an effect is revealed by a comparison of the categories used for estimation by control and experimental groups. Both tended to use response categories which are multiples of 25, but the experimental group used many more—564 to Group C's 459. The difference is significant ($p < .01$). The far boundary of the training scale (300 yd.) appeared to exert an effect on

the judgments of distances greater than this value. Further experiment with the componenets given singly might throw more light on what *S* learns.

Experiment II was designed to discover whether the training received by members of the experimental group increased their sensitivity to small differences in distance magnitudes. Since the DL's for the experimental group were not significantly lower than the control group's, it must be concluded that differentiation within the distance dimension was not increased. It should not be concluded that the relative judgment of distance cannot be improved, however; the amount of practice may have been too little, for *S*s' performance was already quite good and was perhaps at an asymptote. Also, the judgment made in the training situation was not very similar to that made in the test of relative judgment. The training actually was concerned with judgment of grosser distance magnitudes than was the test.

The results of Exp. II do, however, strengthen our assumption that a psychophysical scale exists in which stimulation deriving from a ground surface is correlated with perceptual judgments of greater or lesser distance. Highly typical psychophysical functions were found (see Fig. 2). Since the targets as such provided little basis for a judgment of their distance and a judgment of alignment was impossible, it follows that for any object in contact with the ground the perception of distance of the object may be determined by the impression of distance of the background surface at the point of contact.

For an object *not* in contact with the ground, the perception of distance must depend largely on stimulation deriving from the object itself yielding impressions of edges, depth, etc. The classical list of cues, as well as factors of knowledge and inference, would be relevant. An experiment by Bourdon (**1**; and **10**, p. 670) obtained DL's for judgments of relative nearness and farness of two luminous circles, placed at right angles to one another at distances averaging around 20 meters. The surroundings were dark. The DL's for this judgment were about 22% of the standard distance, compared to 2½% in our study (DL defined as one-half the interval of uncertainty). The absence of stimulation from a ground surface in Bourdon's experiment is probably the principal reason for the difference in results. Convergence, retinal disparity, and motion parallax were all operative to some extent in Bourdon's situation, since when he modified it by restricting the conditions to monocular vision and a motionless head, he obtained completely equivocal judgments.

For a pair of objects in contact with a surface, but located so that the stretch of distance to one coincides or nearly coincides with that to the other, the perception of distance as such will be accompanied or even supplanted by a different type of tridimensional perception, the impression of *in front of* or *behind*. For this judgment, there is a different basis in stimulation. The object behind will be optically above the one in front and vice versa. We cannot agree with Teichner, Kobrick, and Wehrkamp (**8**) as to the prevailing importance of this type of stimulation for impressions of distance. When the two target objects are not optically adjacent, the observer *must* discriminate the respective stretches of distance in order to decide which object is farther or nearer. This is a frequent type of judgment in daily life, and it is probably associated with locomotion of all kinds.

## Summary

The purpose of the two experiments described was to determine the effect of training on (*a*) absolute judgments of distance, in yards, and (*b*) relative (nearer-farther) judgments of distance to variable targets. Training with a scale of distance was given the experimental group in both experiments. A 300-yd. stretch along a grass surface was bounded for *S*, and a 10-yd. unit designated for his scale. Then *S* made corrected fractionation judgments until the ground was divided into 25-yd. intervals. Following training, *S*s of Exp. I were taken to a different field where they made *absolute* estimations of the distance, in yards, to unfamiliar targets at varying distances (52 to 395 yd. away). A control group made the absolute estimations without

previous training. In Exp. II, *S*s were taken to a large field and asked to make *relative* judgments of the distance from *S* to two targets separated by 120°. The standard was set at 50, 100, or 200 yd. from *S*. The method of judgment was a combination of a method of limits and a constant method. A control group made the same judgments without pretraining.

Results of Exp. I indicated that *S*s who received the pretraining were superior to control *S*s in both constant and variable error. Absolute estimation was improved even though *S*s were not tested in the same field where they were trained, the targets were unfamiliar, and the distances varied. It was proposed that *S* learned a scale relating responses, in yards, to gradients of stimulation deriving from the ground surface.

Pretraining with a scale of distance did not, however, lower DL's for distance in Exp. II. Sensitivity of the psychophysical relationship is apparently not increased by this training, although the yard-responses become more accurately tied to it. The DL for distance was about 2½% of the standard distance and was constant for the three standard distances employed. The fact that consistent psychophysical functions of the expected kind were found with wide angular separation of the standard and comparison target strengthens the hypothesis that gradients of stimulation made available by the ground surface itself are in correspondence with impressions of distance of varying magnitudes.

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# PREFERRED PATTERNS OF MOTOR AND VERBAL RESPONSES [1]

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Preferences for certain responses and sequences of responses have been identified in numerous psychophysical experiments (**3, 6, 7**). Such preferences have also been observed when *Ss* have attempted to produce a random series of numbers (**1**). If response preferences are known, the task of predicting future responses becomes less difficult. The purpose of this experiment was to measure the predictability resulting from the response and sequential preferences displayed in a series of motor and verbal responses, and to identify some of the sources of this predictability.

## METHOD

The *Ss* were presented with one of two panels of eight discs equally spaced to form the outline of either a square or a circle. A schematic representation of these panels is shown in Fig. 1. The separate discs on each panel are identified by number. No numbers appeared on the actual panels. The panels were mounted on a table at an angle of 60° from the horizontal.

The *Ss* were instructed to generate a series of responses by repeatedly selecting the different discs in a random manner so that in a long series all discs would be selected about equally often with no system in the sequence of selections. Selections were made by touching metal discs with a stylus or by reporting code names printed on paper discs. Both methods of response were used with both of the panels. Each of 32 *Ss* made 2,800 responses under one of the four resulting conditions. A short sample of a random series was produced for all *Ss* before they began their responses. Brief rest periods were permitted after every 700 responses. The total experimental period was divided, therefore, into four series of 700 responses each. All *Ss* were right-handed, male college students who had had little statistical training.

The circular figure was 6 in. in diameter when measured at the center of the discs. The square figure was 6 in. on a side. Each disc was 1 in. in diameter.

Motor responses were recorded on the tape of an Esterline-Angus Operations Recorder. Each disc was wired to a separate pen. Verbal responses were recorded on magnetic tape and later transcribed. All responses were paced by a metronome operating at a rate of 50 beats per min. This rate was slow enough to permit the unhurried completion of all possible sequences of two responses. Actually the rate was slower than that which some preliminary *Ss* produced without pacing.

Two codes were used to identify the discs chosen by means of the verbal method. The first consisted of eight relatively meaningless three-letter combinations. The second code was made up of eight different consonants. These particular letter combinations and consonants were chosen because they were easy to pronounce and were reasonably easy to distinguish during the transcription. The codes were printed on white cardboard discs that were placed over the metal discs used with the motor response. Those *Ss* who used the verbal response worked with the letter combinations during the first and fourth

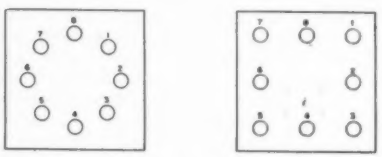


FIG. 1. Diagram of the panels.

[1] This research was carried out under Contract N5ori-166, Task Order 1, between the Office of Naval Research and The Johns Hopkins University. This is Report No. 166-I-194, Project Designation No. NR 145-089, under that contract. Aid in the collection and analysis of the data was provided by Miss Frances Wolfram, Miss Sue Wollenberg, and Mr. Emanuel Averbach. The essentials of this paper were presented at the 1954 meeting of the American Psychological Association.

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series of responses. During the second and third series, they worked with the consonants. When a code appeared for the second time, the positions of all discs were changed so that each code name was centered between a different pair of immediately adjacent code names.

## Results

In analyzing the results a tabulation was made of the frequency of occurrence of all possible responses, pairs of responses, and response triads for each of the four experimental conditions. Pairs and triads were counted in a way that produced overlapping. In a sequence of responses represented by the numbers 1, 2, 3, 4, for example, three pairs—1–2, 2–3, and 3–4, and two triads—1–2–3, and 2–3–4 were counted.[3] Sequential counts were adjusted at the end of each series of 700 responses by adding two extra responses made by the *S*s before they began a rest period.

The predictability of the responses was measured for each *S* individually by means of the multivariate information analysis described by McGill (**5**).[4] In this paper, however, the term "predictability" is substituted for McGill's "transmitted information."

*Response predictability.*—If *S*s had responded in a random manner, the various discs would have been chosen equally often, and the total uncertainty in the responses would have been 3 bits. Actually *S*s did not choose the discs equally often, but the mean reduction in uncertainty (predictability) associated with knowledge of the average frequency with which the various responses were made was not very great. Table 1 shows the mean amounts of predictability for each of the experimental groups. Apparently predictions made about future responses will not be very accurate when only this much is known about past responses. Surprisingly enough, however, there are significant differences between the amounts of predictability associated with the different groups. Motor responses were significantly more predictable than verbal responses when nothing was known about response sequences. The significance of this difference was demonstrated by Wilcoxon's *T* test for groups of replicates (**8**) ($P < .02$), and by a conventional analysis of variance ($P < .01$). The effect of the difference in figures was not significant.

TABLE 1

Amount of Predictability When Only the Average Response Frequency is Known

(Maximum = 3 bits)

| Panel | Response Method | |
|---|---|---|
| | Motor | Verbal |
| Square | .01922 | .00603 |
| Circle | .01125 | .00404 |

Although little is known about the distribution of information scores, the homogeneity of the variance estimates from these particular scores was established by means of Bartlett's test.

*Response preferences.*—Figure 2 shows the mean frequency with which the various responses were made under each of the experimental conditions. The positional numbers correspond to the numbers on the panels in Fig. 1. According to Friedman's nonparametric analysis of variance (**2**), there are significant differences among the response preferences dis-

[3] The counting was done on a special sequential tabulator designed and constructed at the Engineering Laboratory, Institute for Cooperative Research, The Johns Hopkins University.

[4] The information analysis was carried out with the aid of unpublished tables of $n \log_2 n$ provided by Dr. W. J. McGill.

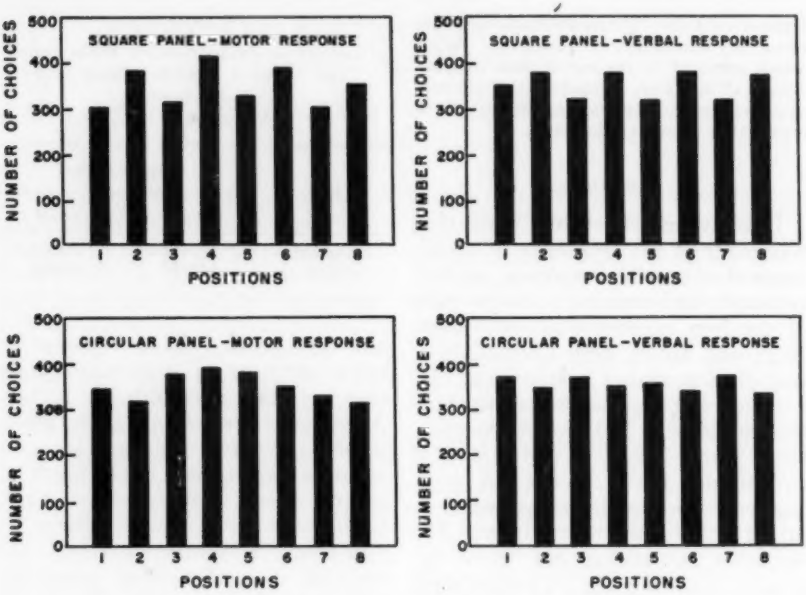


FIG. 2. Mean frequencies with which the various discs were chosen.

played within each condition ($P < .05$).

Although the amount of predictability resulting from knowledge of the average frequency with which the responses were made is very low, it is easy to identify some of the sources of this predictability. In Fig. 2 three sources of predictability are apparent. (*a*) With the square panel the mid-points of the figure (even numbers) were more frequently chosen than the corners (odd numbers) regardless of the response method used. (*b*) The *S*s who used the motor response showed a relatively consistent gradient of preference extending from the most preferred positions at the bottom of the figures to the least preferred positions at the top. This tendency is superimposed on the preference for the mid-points and the aversion for the corners that characterized the motor responses made with the square panel. The preference for the lower positions did not appear with the verbal responses. (*c*) When the verbal response method was combined with the circular panel a slight preference was shown for the odd-numbered discs. No consistent preference was shown for the discs on either the right or the left side of the panels.

These results could have occurred if *S*s had been completely random in their responses throughout as many as three of the four series of 700 responses and decidedly nonrandom in the remaining series. Some measure of the consistency of preferences throughout the entire response period is required. To provide this measure rank-difference correlations were computed showing the relationship between the frequencies with which the various discs were chosen in the different series. These correlations were calculated for each *S* indi-

vidually. If an *S* chose certain discs frequently and other discs infrequently in one series and showed the same tendencies in another series, some degree of correlation between the two series would result. Table 2 shows the median correlations for the eight *S*s in each group. It is obvious that *S*s responded with a fair degree of consistency throughout the entire experimental period. Preferences displayed with the motor response and the square panel appear to be somewhat more consistent than those associated with the verbal response and the circular panel.

*Sequential predictability.*—The amount of predictability was low when only the average frequency of the various responses was known. Predictability was greatly increased when response sequences were included in the analysis. Figure 3 shows the amount of predictability obtained when knowledge about previous responses was used for prediction. In the figure the data for all four experimental groups are combined.

When the first previous response

TABLE 2

MEDIAN RANK-DIFFERENCE CORRELATIONS SHOWING THE CONSISTENCY OF RESPONSE PREFERENCES

| | Motor Response Series | | | | Verbal Response Series | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | | I | II | III | |
| *Square* | | | | | | | | |
| II | .81 | | | II | .80 | | | |
| III | .66 | .86 | | III | .69 | .56 | | |
| IV | .86 | .91 | .82 | IV | .64 | .78 | .77 | |
| *Circle* | | | | | | | | |
| II | .60 | | | II | .61 | | | |
| III | .74 | .69 | | III | .58 | .58 | | |
| IV | .70 | .50 | .81 | IV | .47 | .49 | .52 | |

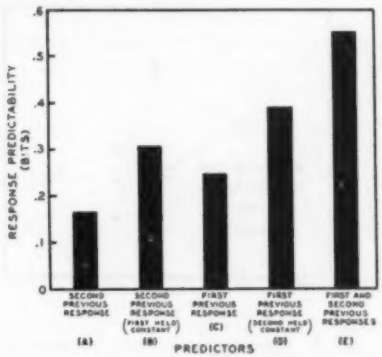


FIG. 3. Amount of predictability resulting from knowledge of previous responses.

(*C*) was identified, the amount of predictability was almost .25 bit. When this response and the second previous response were both used as simultaneous predictors (*E*), the average predictability reached .55 bit. This is quite an increase over the predictability associated with just the average frequency with which the various responses were made. It is clear that most of the predictability in these responses is related to preferences for sequences rather than preferences for the responses themselves.

Figure 3 indicates that a greater amount of predictability resulted from knowledge of the first previous response alone (*C*) than from knowledge of the second previous response alone (*A*). Garner and McGill (**4**) have shown, however, that in dependent time series the amount of predictability obtained by adding the separate predictabilities from the two previous responses alone will not be equal to the total predictability from the two previous responses considered simultaneously (*E*). This is shown in Fig. 3 by the fact that $A + C$ does not equal *E*. An interaction term is responsible for this discrepancy, but the interaction cannot be interpreted

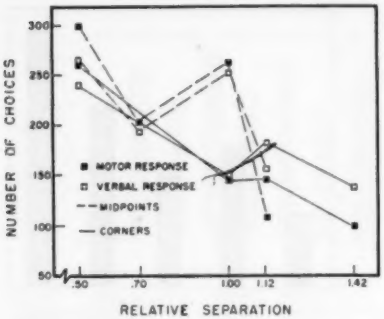


FIG. 4. Relationship between frequency of occurrence of response pairs and the relative distance between the members of the pairs for the square panel. The separation is expressed in proportion to the length of the sides of the square. Pairs beginning at a mid-point are considered separately from those beginning at a corner.

exactly because it includes a covariance term of unknown size.

Actually *E* in Fig. 3 is the sum of either *A* and *D* or *B* and *C*. Because of this it is impossible to say that either the second previous response or the first previous response contributes the greater amount of predictability when the two predictors are used simultaneously. If *E* is considered as the sum of *A* and *D* then the first previous response contributes the greater share of predictability. However, if *E* is considered as the sum of *B* and *C* then the second previous response contributes the greater share of predictability.

*Sequential preferences.*—Some of the sources of predictability associated with response sequences can be easily identified.

1. The frequency of occurrence of various pairs of responses is inversely related to the linear distance between the discs making up the pairs. This effect is shown in Fig. 4 for the square panel and in Fig. 5 for the circular panel. In both of these figures the separations between the members of the response pairs are expressed as proportions of the 6-in. separation that was common to the two stimulus panels. This is done because the absolute values of the separations depend upon the over-all size of the stimulus configuration. These curves have been corrected in order to compensate for the fact that there are more possible different pairs of responses for certain separations than for others. For example, among the pairs beginning at a corner of the square panel there are eight possible pairs with a relative separation of .50 but only four pairs with a relative separation of 1.42. To correct for this difficulty the mean frequency of occurrence of response pairs in each category of separation has been divided by the smallest whole number directly proportional to the number of possible response pairs in that category.

2. A second source of predictability is the relatively high preference for response pairs that bisect the stimulus panels, except on the diagonal. This effect appears in Fig. 4 at the relative separation of 1.00 for responses beginning at a mid-point. The pairs with a relative separation of 1.42 also bisect the

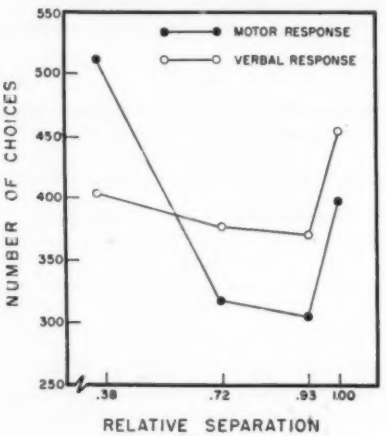


FIG. 5. Relationship between frequency of occurrence of response pairs and the relative distance between the members of the pairs for the circular panel. The separation is expressed in proportion to the diameter of the circle.

panel, but this is a diagonal bisection. No other bisections are possible for responses beginning at a corner. Figure 5 shows the same effect for responses obtained with the circular panel. Again, pairs that bisect the stimulus panel were chosen more frequently than would be predicted from knowledge of the separation involved.

3. Predictability was increased by a preference for clockwise and counterclockwise triads made around the perimeter of the figures. In this analysis only those triads involving a constant direction and immediately adjacent discs were counted. The results are shown in Table 3 in which a comparison is made between the square and circular panels. From a total number of 44,800 triads produced with each figure, 700 would be expected to appear in each cell of Table 3 if the series were random. Actually these triads were produced from about 2.5 to 4 times as often as would be expected. This result is related, of course, to the preference shown for response pairs separated by short distances. The tendency for a greater number of these triads to be associated with the square panel is not statistically significant. The slight preference for counterclockwise sequences is also not significant.

4. Another source of predictability was a consistent aversion for certain sequences. Response pairs or triads involving double or triple repetition of the same response were rare. In a random series 5600 repetitive pairs from the total of 44,800 response pairs for each response method, and 700 repetitive triads from the total of 44,800 triads would be expected to appear. Table 4 shows that a much smaller percentage of these sequences was obtained than would be produced in a random series. This result is similar to one observed by Chapanis in his random-number experiment (1). The tendency to avoid these repetitive sequences was much greater for those *S*s who used the verbal response than for the *S*s who used the motor response.

These sources do not account for all of the predictability associated with response sequences, but it is difficult to identify additional meaningful sources because of the complexity of the relationships.

TABLE 3

OBTAINED NUMBER OF UNIDIRECTIONAL TRIADS MADE AROUND THE PERIMETER OF THE FIGURES

(Expected number in each cell = 700)

| Panel | Direction | |
|---|---|---|
| | Clockwise | Counterclockwise |
| Square | 2589 | 3076 |
| Circle | 1954 | 1835 |

TABLE 4

OBTAINED NUMBER OF REPETITIVE RESPONSE PAIRS AND TRIADS EXPRESSED AS A PERCENTAGE OF THE EXPECTED NUMBER

| Sequence | Response Method | |
|---|---|---|
| | Motor | Verbal |
| Pairs | 29 | 6 |
| Triads | 32 | 1 |

## SUMMARY

The *S*s were instructed to produce a random series of responses by repeatedly selecting single discs from a set of eight discs arranged to form the outline of either a square or a circle. Selections were made by touching metal discs with a stylus or by reporting code names printed on paper discs.

The predictability of the responses was measured by means of a multivariate information analysis. It was found that by far the greatest amount of predictability resulted from knowledge about sequences of responses rather than knowledge about the average frequency with which the various responses were made.

It was possible to identify some of the sources of this response predictability. Predictability was increased by *S*s' consistent preferences for certain responses and sequences of responses. The particular preferences displayed were influenced by the type of stimulus figure and the method of response used.

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# RETROACTIVE AND PROACTIVE EFFECTS UNDER VARYING CONDITIONS OF RESPONSE SIMILARITY [1]

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The usefulness of response generalization as an explanatory concept for results of certain verbal learning experiments has been well demonstrated (**5, 6, 9, 11**). This theory can be summarized briefly. If Response B is learned to Stimulus A, the associative strength between Stimulus A and a given response will be directly related to the degree of similarity between this response and Response B. Thus Response B′, which is highly similar to Response B, is said to derive generalized reinforcement when Response B is directly reinforced. On the other hand, a response which has little similarity to B will derive little or no generalized reinforcement. This decrease in associative strength as the similarity between the directly reinforced response and the generalized response decreases, defines a gradient of response generalization. Such a gradient has been demonstrated empirically for verbal materials (**10**).

Certain transfer effects can readily be handled by these notions. Assume *S* learns A–B (first list) and then A–B′ (second list with identical stimuli and highly similar responses). This is a paradigm for high positive transfer and such transfer is predicted directly from the theory. As *S* learns A–B, the gradient of response generalization around B includes Response B′. Therefore, the learning of A–B provides generalized reinforcement for A–B′ and consequently, when *S* begins to learn A–B′, there is already a certain degree of associative strength between A and B′. Positive transfer results. If there is little or no similarity between the first- and second-list responses, no appreciable positive transfer should be measured because no generalized reinforcement should occur. (Other mechanisms may, of course, produce positive transfer.)

A concept implicit in the previous discussion is that of the summation of direct and generalized reinforcement. Explicitly stated this idea holds that direct and generalized reinforcement are additive regardless of the temporal sequence in which they are received. The purpose of the present research is to test an implication of this hypothesis. We have seen that A–B′ derives generalized associative strength when A–B is being learned. Now, in addition, when the second list, A–B′ is being learned, A–B (first list) should receive generalized reinforcement. Consequently, Response B should have a greater associative strength to A than should B′ following the learning of A–B′ even though both lists have been learned to the same apparent criterion. The indicated paradox of different associative strengths following learning to identical criteria is resolved when we note that the generalized reinforcement received by Response B′ came *before* the learning criterion was attained, while the generalized reinforcement

[1] This article is based on a dissertation submitted to the Graduate School, Northwestern University, in partial fulfillment of the requirements for Doctor of Philosophy. The writer is indebted to Dr. Benton J. Underwood for his many helpful suggestions.

which Response B received came *after* the learning criterion was attained. As before, it is clear that if there is little similarity between the responses, very little difference in response strengths of the two lists will be anticipated.

We will now extend the paradigm by adding a third list. According to the hypothesis, when the stimuli are identical and responses highly similar, generalized reinforcement will accrue to the second and third list while List 1 is being learned, to the first and third while List 2 is being learned, and to the first and second while List 3 is being learned. Furthermore, it can be seen that, according to the theory, if all three lists are taken to the same criterion of performance, the actual response strength of the first list should be greater than that of the second, and the second greater than that of the third. These differences in response strength will be less the less the similarity between the responses in the three lists. The present experiments make tests of these predictions by using a retroactive inhibition (RI) paradigm, and a proactive inhibition (PI) paradigm.

From several studies (**2, 4, 7**) we know that for short retention intervals RI is greater than PI when the A–B, A–C paradigm is used. However, as already indicated, when response similarity is low, response generalization will have little effect. Now, for reasons referred to above, if we increase the response similarity for three successively learned lists, the strength of the first-list response will become greater than that of the second, and the second greater than that of the third. The first implication of these ideas is that as response similarity increases, RI will decrease, for as response similarity increases, the strength of the first list (the list to be recalled) increases relative to the strength of the other two lists. The second implication is that as response similarity increases, PI (forgetting of the third list) will increase, for relative to the strength of this third list the strengths of the first and second lists will become greater, hence should interfere more and more with the recall of the third. The present experiments will test these two deductions.

It must be clear that our proposal makes no pretense of accounting for total measured RI and PI, and is not considered a complete theory of RI and PI. We are using the RI andPI paradigms to test the hypothesis of the summation of direct and generalized reinforcement, and this hypothesis leads clearly to the predictions that: (*a*) as response similarity increases, RI will decrease, and (*b*) as response similarity increases, PI will increase. We are using a three-list situation in order to maximize the hypothesized effects, and, of course, (*c*) the amount of positive transfer will increase directly as a function of response similarity.

## Method

One of the underlying assumptions of the introductory discussion was that the degree of learning for all lists would be equal at the end of learning, i.e., response similarity but not degree of learning would be varied. An attempt to equate the degree of learning at recall encounters a methodological difficulty which is discussed in detail elsewhere (**8**, p. 529). The difficulty encountered is that the degree of learning evidenced on any trial is not what was learned on that trial but rather the degree of learning attained at the end of the previous trial. Thus in a comparison of two lists which reach the same learning criterion at markedly different rates, e.g., high positive transfer from List 1 to List 2, the apparent equality in learning at the criterion reflects the fact that equivalent degrees of learning were reached on the previous trial. However, if it were possible to stop the learning of the lists one trial before *S* reached the learning criterion, the degree of learning at recall, i.e., the

next trial, could then be equated for groups of *Ss*. To accomplish this a pilot study was conducted to determine the acquisition functions of lists which were to be employed in the major experiment.

*Pilot Study*

The pilot study consisted of one practice day and four experimental days for each *S*, and during each experimental day *S* learned three lists of eight paired associates. The four experimental sessions included a control condition where the similarity between stimuli and responses of all three lists was minimal;and three conditions of varied response similarity. In these three conditions the stimuli of each set of three lists were identical while the degree of interlist response similarity was varied from highly similar responses in one condition to responses with a medium degree of similarity in a second condition to completely dissimilar responses in the third condition. These conditions of varying response similarity will be referred to as the High, Medium, and Low conditions. In all four sets of lists the intralist similarity was as low as could be achieved by careful inspection of the items. Thus we have four sets of three lists, which are presumed to vary only in interlist response similarity.

*Materials.*—Three lists of eight two-syllable paired adjectives were learned by *S* during each experimental session. These lists were constructed from adjective materials prepared by Haagen (1) and Melton (3), and items were chosen on the basis of degree of similarity with familiarity constant. The differences in similarity between the different conditions may be illustrated with groups of paired adjectives taken from the lists. It will be remembered that the lists in the similarity conditions have identical stimuli and responses varying in similarity, while in the Control condition lists are as dissimilar as possible.

| *Condition* | *List 1* | *List 2* | *List 3* |
|---|---|---|---|
| High | discreet-ailing | -unwell | -sickly |
| Medium | rustic-solvent | -liquid | -flowing |
| Low | select-intense | -taboo | -dismal |

Both the conditions of similarity and the lists within a condition were counterbalanced, with 24 *Ss* required for complete counterbalancing of conditions.

*Procedure.*—The paired adjectives were presented on a Hull-type memory drum with the standard rate of 2 sec. for the stimulus followed by 2 sec. for the stimulus and response together. The intertrial interval was 4 sec., and a 60-sec. rest interval was given between the learning of the lists within a condition to allow time to change tapes. Five different orders of presentation of each list were used to avoid serial learning. Each list was learned to a criterion of one perfect trial.

On the practice day *S* learned two lists. The similarity relationships between the two lists were a composite of all four experimental conditions and the learning criterion was one perfect recitation for each list.

The 24 *Ss* used in the pilot study were obtained from introductory psychology courses and were well practiced since all had served in a nonsense-syllable experiment prior to serving in this experiment.

*Determination of learning criteria.*—Logarithmic curves were fitted to the acquisition functions for each of the lists in all four experimental conditions. The least-squares method was used in the determination of the curves. Cut-off points, to equate learning in the main experiment, were determined from the logarithmic curves fitted to each list. The cut-off points for all lists were determined so that an average of seven correct responses would be obtained on the next trial.

*RI and PI Experiments*

Two experiments were conducted, one employing the operations used in producing RI and the other used in producing PI. These two experiments (Exp. RI and Exp. PI) were exactly the same except for the list recalled. Both experiments used the verbal materials and employed procedures which were exactly the same as those used in the pilot study with but two exceptions: (*a*) learning criteria were different for each list in every condition and were determined by the learning curves obtained from the pilot study, and (*b*) *Ss* in Exp. RI recalled List 1 and *Ss* in Exp. PI recalled List 3. Following learning, *Ss* were given five recall trials; the interval between learning and recall of the first list (in Exp. RI) and the third list (in Exp. PI) was 18 min. The interval between the learning and recall of List 1 in Exp. RI was filled both by the learning of Lists 2 and 3 and by a cartoon-rating task while in Exp. PI the interval was completely filled by the cartoon rating.

*Practice day.*—One practice day was given with *S* learning two lists and recalling either the first (RI *Ss*) or the second (PI *Ss*). The first list was always learned to one perfect recitation while the second list was learned to an arbitrary criterion of six correct on one trial plus the presentation of four items on the following trial. After a short rest interval *S* was given five additional trials on the first list (Exp. RI) or the second list (Exp. PI).

*Learning criteria.*—The learning criteria for Exp. RI and PI were determined from the

TABLE 1

MEANS AND *SD*'S OF NUMBER OF TRIALS IN LEARNING TO THE CRITERION OF FIVE CORRECT RESPONSES ON A SINGLE TRIAL

| Condition | List 1 | | List 2 | | List 3 | | $100\frac{\text{List 1}-\text{List 3}}{\text{List 1}}$ |
|---|---|---|---|---|---|---|---|
| | Mean | *SD* | Mean | *SD* | Mean | *SD* | |
| Low | 6.25 | 3.94 | 5.48 | 2.79 | 4.36 | 2.22 | 30 |
| Medium | 5.57 | 3.44 | 4.42 | 2.26 | 3.42 | 1.58 | 38 |
| High | 5.67 | 2.71 | 3.77 | 2.31 | 2.61 | 1.58 | 54 |
| Control | 4.29 | 2.20 | 3.46 | 1.98 | 2.71 | 1.19 | 37 |

learning curves derived from the pilot study data, and were fixed so that the apparent degree of learning for all lists would average seven correct items on a hypothetical "next trial." A combination of learning criteria and trials was used to determine the degree of learning necessary. For example, the learning criterion for one of the lists was six correct items on one trial, one additional trial, and the presentation of a single item on the next trial. Thus if *S* had had one additional trial, the degree of learning of this list would have been seven items correct on the average. A criterion of seven items correct rather than eight (one perfect recitation) was used so that the possible summative effects of direct and generalized reinforcement upon the first list of the High condition and possibly the first list of the Medium condition could be measured. It was felt that the effects of generalized reinforcement derived from the learning of subsequent lists would not be readily apparent if the first list was taken to a very high degree of learning.

*Miscellaneous.*—The *S*s used in Exp. RI and PI were obtained from introductory psychology courses and had served in a nonsense-syllable experiment prior to serving in this experiment. Again 24 *S*s served in each experiment, permitting a counterbalancing procedure which was exactly the same as that employed in the pilot study. The cartoon-rating task was used as the rest-interval activity throughout.

## RESULTS

*Equality of groups.*—The practice day offers a fair measure of the comparability of the *S*s in Exp. RI and PI. The difference between the two experiments in the mean number of trials to attain the criterion for the practice list was $1.00 \pm 1.10$ ($t = .91$).

*Transfer effects.*—The learning data of Exp. RI and PI have been combined to evaluate transfer effects and are presented in Table 1. The data in Table 1 are based on trials to reach a criterion of five correct responses on a single trial. It was necessary to use this criterion because this was the highest recorded number of correct responses on the third list in the High condition, as determined from the pilot study. As can be seen from Table 1, when stimuli are identical and response similarity is varied, amount of transfer is a direct function of response similarity. Furthermore, this relationship holds for the learning of both the second and third lists. The transfer effects in each of the conditions are clear-cut, but not all positive transfer can be clearly attributed to the effects of the independent variable, for there were significant amounts of learning-how-to-learn transfer. Since there were significant practice effects between days, practice effects may also have occurred within days thus increasing the amount of positive transfer obtained. The data presented in Table 1 closely parallel those obtained from the pilot study and for this reason the pilot study results will not be reported.

The Control lists were easier to learn than the lists of the other conditions. The difference in difficulty was apparent in the learning functions of Exp. RI and PI and of the pilot study. Since we know little about the relationship between difficulty of

material learned and recall of this material, we have not included the recall scores of the Control condition in our analyses of recall.

The transfer data presented above give support to the theory. However, further analysis of the learning data was done by means of an item analysis. The results obtained from this analysis are in agreement with the theory and closely parallel an item analysis previously reported (9). It is apparent from the item analysis and from the gross transfer data that the theory may properly be extended to predict transfer results in the three-list situation.

*RI and PI effects on first recall trial.*—On the basis of the pilot-study data, the learning of each list was stopped so that on the next trial the average number of correct responses would be seven items. It was on the seven-item-correct basis that relative percentages of RI and PI were computed for the first recall trial. The percentage forgotten was determined by subtracting the mean number of items recalled from seven and dividing this result by seven. These data are presented in Fig. 1. They indicate that the amount forgotten in Exp. RI decreases from 80% in the Low condition to 48% in the High condition. This decrease in amount forgotten is in agreement with response generalization theory, for the theory states that the associative strength of List 1 will increase as a result of the generalized reinforcement provided for this list by the subsequent learning of Lists 2 and 3. The data from Exp. PI do not provide results which are in complete agreement with the theory. On the first recall trial the amount forgotten in the High condition was not greater than the amount forgotten in the Low condition, as would be predicted by the theory.

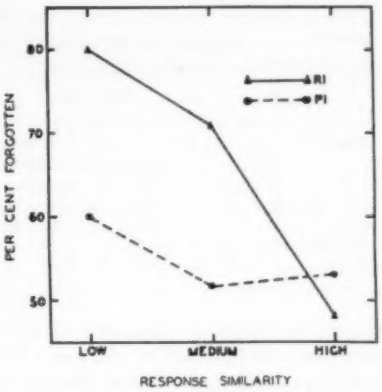


FIG. 1. Percentage of relative RI and PI as a function of response similarity.

*Statistical analysis of recall.*—Analyses of variance of the first recall trial and of all five recall trials are pre-

TABLE 2

ANALYSIS OF VARIANCE OF RECALL SCORES

| Source | *df* | First Recall Trial | | All Five Recall Trials | |
|---|---|---|---|---|---|
| | | *MS* | *F* | *MS* | *F* |
| Exp. | 1 | 21.78 | 6.83* | 65.34 | — |
| Subjects/Exp. | 46 | 3.19 | | 71.68 | |
| Similarity | 2 | 22.22 | 11.63** | 133.56 | 8.70** |
| Similarity × Exp. | 2 | 12.01 | 6.29** | 206.72 | 13.46** |
| Days | 2 | 1.06 | — | 12.58 | — |
| Days × Exp. | 2 | .72 | — | .70 | — |
| Residual/Exp. | 88 | 1.91 | | 15.36 | |
| Total | 143 | | | | |

* $P = .05$.
** $P = .01$ or better.

TABLE 3

MEANS AND *SD*'S OF NUMBER OF CORRECT ITEMS IN RECALL

| Similarity | First Trial | | | | All Trials | | | |
|---|---|---|---|---|---|---|---|---|
| | RI | | PI | | RI | | PI | |
| | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* |
| Low | 1.37 | 1.28 | 2.83 | 1.31 | 22.46 | 6.76 | 26.88 | 5.51 |
| Medium | 2.13 | 1.47 | 3.33 | 1.63 | 25.54 | 6.08 | 28.17 | 4.82 |
| High | 3.67 | 1.65 | 3.29 | 1.57 | 29.67 | 5.51 | 26.29 | 5.28 |

sented in Table 2. In both of these analyses the interaction between Experiments (RI and PI) and Similarity is significant at the .01 level of confidence. Similarity is also significant at the .01 level for both analyses. However, Experiments is significant at the .05 level for the first recall trial but the difference between experiments in total number of items given correctly for all five recall trials is not significant.

Separate analyses of variance were performed on both Exp. RI and PI. In Exp. RI $F$'s of 17.32 ($P < .01$) and 19.05 ($P < .01$) were obtained for the first recall trial and all five recall trials, respectively, while $F$'s of .94 ($P > .05$) and 1.58 ($P > .05$) were obtained for Exp. PI. Clearly, RI was related to response similarity, while PI was not. Means and *SD*'s obtained from the Exp. RI and PI recall data for the first recall trial and for all five recall trials are presented in Table 3. Two $t$ tests computed on total number of items given correctly for all five recall trials indicate that RI was significantly greater than PI in the Low condition ($t = 2.43$, $p < .05$) and PI was significantly greater than RI in the High condition ($t = 2.13$, $p < .05$).

*Intrusions during recall.*—Intrusions occurring during recall are presented in Table 4. The intrusions for Exp. RI represent items from List 2 and List 3 which were given during the recall of List 1, while the intrusions in Exp. PI are items from List 1 and List 2 which were given during recall of List 3. The number of intrusions in Exp. RI decreased as response similarity increased, and the number of intrusions in Exp. PI increased as response similarity increased. In general, these results are consistent with the theory. The theory would predict that as response similarity increases the associative strength of List 1 responses will increase and consequently, there should be an attendant decrease in the number of List 2 and List 3 responses given during the recall of List 1 (RI) and an increase in the number of List 1 and List 2 responses given during the recall of List 3 (PI).

## DISCUSSION

While we have been unable to make direct measurements of the associative strengths of different responses to identical stimuli, we have been able to determine the relative associative strengths of first or last list learned as a function of degree of response similarity. It is with

TABLE 4

TOTAL INTRUSIONS DURING RECALL

| Similarity | First Trial | | All Trials | |
|---|---|---|---|---|
| | RI | PI | RI | PI |
| Low | 30 | 11 | 42 | 16 |
| Medium | 26 | 15 | 48 | 23 |
| High | 24 | 20 | 33 | 34 |

reference to these functions that our predictions have been made, and we have attempted to test these predictions by use of RI and PI paradigms.

The data obtained from Exp. RI and PI were favorable to a response-generalization interpretation. This was true in the case of transfer and intrusion data as well as in the case of the Exp. RI recall scores. However, PI did not show a significant increase as response similarity increased.

Thus in Exp. PI the intrusion data at recall are in agreement with the theory while the PI recall scores are not. We have no completely satisfactory solution to this lack of consistency. One possibility is that differentiation of the responses in one list from those of another is greater the more recently the list is learned. The fact that total intrusions for Exp. RI was greater than for Exp. PI suggests that some mechanism is operating whereby *S* has less of a tendency to respond erroneously when recalling the third list than when recalling the first. If this factor of differentiation among lists is an important one, we would expect that with a longer interval, say 24 hr., differentiation would decrease to a low level so that PI would be found to increase with increased response similarity as predicted.

Another factor that may be involved is unlearning (4), although by use of this construct we have been unable to arrive at our obtained results without a considerable number of additional assumptions. For the present we feel that the PI results indicate a limit to the usefulness of the theory.

## Summary

On the basis of a theory of response generalization it was predicted that in learning successive paired-associate lists the associative strength of the first list learned would increase as response similarity increased. This increase in associative strength would result in a decrease in retroactive inhibition (RI) and an increase in proactive inhibition (PI).

Two experiments were conducted, one dealing with RI and the other dealing with PI. In both experiments there were three conditions with identical stimuli and with response similarity varying from high to medium to low. A control condition employed dissimilar verbal materials. In Exp. RI the first list was given five additional trials 18 min. after it was learned, and in Exp. PI the last list learned was given five additional trials 18 min. after it was learned.

The results showed: (*a*) positive transfer in learning three lists increased as a function response similarity; (*b*) RI decreased as response similarity increased; and (*c*) PI did not increase as response similarity increased. Support for response-generalization theory was found in results (*a*) and (*b*) and in the intrusion data at recall.

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# STUDIES OF DISTRIBUTED PRACTICE: XIV. INTRALIST SIMILARITY AND PRESENTATION RATE IN VERBAL-DISCRIMINATION LEARNING OF CONSONANT SYLLABLES [1]

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In an earlier study it was found that neither intralist similarity nor intertrial rest interval was a significant variable in learning adjectives in a verbal-discrimination task (**10**). In the present experiments we have again examined the influence of these two variables but under conditions designed to make the task a much more difficult one than in the previous study. In making these changes toward greater task difficulty we had two major objectives in mind. First, we wished to make a fairly critical test of the influence of intralist similarity on learning and retention of verbal-discrimination lists. Since serial and paired-associate learning rates can be markedly influenced by intralist similarity, we felt that this variable must be more fully explored in verbal-discrimination learning. Consequently, we have set up two rather extreme cases of intralist similarity among consonant syllables. Secondly, there is some evidence in serial and paired-associate learning that the more difficult the task the more likely it is that distributed practice will facilitate learning. While this evidence does not include increase in difficulty due to intralist similarity (e.g., **6**), it does include increases in difficulty produced by decreased meaningfulness (**4**) and increase in rate of presentation (**1, 2**).

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The three experiments reported here may be considered in pairs. There are two experiments in which the tasks represent two extremes of intralist similarity with presentation rate constant, and two experiments in which similarity is constant but presentation rate different. Within all experiments intertrial interval is varied.

## Procedure

*General design.*—Three separate groups of 36 *Ss* were used, one group for each of the three experiments. All *Ss* were students taking courses in undergraduate psychology. Within each experiment each *S* served in three conditions differentiated only by length of intertrial rest, namely, 4, 30, and 60 sec. In Exp. 2L the presentation rate was 2 sec. for the pair of words, 2 sec. for showing the correct response, and intralist similarity was low (L). In Exp. 2H the presentation rate was the same as in Exp. 2L but the intralist similarity was high (H). In Exp. 1.5H the presentation rate was 1.5 sec. for the pair of words, 1.5 sec. for showing the correct response, and the lists were the same as in Exp. 2H. In all three experiments the lists were learned to one perfect trial with recall and relearning to one perfect trial after 24 hr. Within each experiment the three conditions of intertrial rest and the three lists were counterbalanced in $3 \times 3$ greco-latin squares as in other studies in this series.

*Materials.*—The lists consisted of 14 pairs of consonant syllables. Most of the syllables had from 42% to 53% association value as determined by Witmer (**12**). In order to meet all of the restrictions on the use of a specified number of consonants, it was necessary to use some syllables with 38% association value. Such instances were rare and randomly occurred at both levels of similarity.

Each list in Exp. 2L (low intralist similarity) used 18 consonants. Since the consonants *V*, *W*, and *Y* were never used, the same 18 conso-

nants appeared in each of the three experimental lists. With 14 pairs of syllables per list, 84 consonants are required for each list. None of the 18 consonants was used less than four times in a list nor more than six times. Each high-similarity list (Exp. 2H and 1.5H) was made up of only nine consonants. Each consonant appeared not less than eight times and not more than 10 times. Six of the nine consonants used in a list were also used in one other list. Three of the nine were unique to the list. All consonants in both high- and low-similarity lists appeared about equally often in both correct and incorrect members of the pairs.

It should be noted that the high intralist similarity produced by these rules resulted in similarity not only obtaining between the two syllables in a pair but also among pairs. It also should be noted, as discussed in detail elsewhere (9), that high intralist similarity produces low interlist similarity whereas low intralist similarity produces high interlist similarity. The implications of this factor for the present experiment will be discussed later.

*Details.*—The syllables were typed in pairs, one above the other, on white vellum tape and presented on a Hull-type memory drum. The particular syllable of a pair which was called correct was randomly selected. Each list was presented in three different orders to minimize serial effects. During a given order, half of the syllables which were correct appeared as the upper member of the pair and half as the lower member. The correct member of a pair appeared randomly in the upper or lower position to prevent learning based on position cue.

A spelling and noncorrection procedure was used. The *S*s were instructed to begin anticipating on the first trial. We would, of course, expect an average of seven items to be correctly anticipated by chance. All intertrial intervals longer than 4 sec. were filled with symbol cancellation (5).

All *S*s learned the same 14-pair practice list on the day preceding the first experimental session. This practice list was of moderate intralist similarity (in comparison to the lists used in Exp. 2L and 2H) since 12 different consonants were used in its construction. It was presented with a 30-sec. intertrial interval at the rate to be used in the particular experiment.

## Results

The basic data for the three experiments are given in Table 1. The results for learning, recall, and relearning will be considered separately.

*Learning.*—A comparison of Exp. 2L and 2H shows the influence of intralist similarity on learning. Under all three intertrial intervals more trials were required to learn the lists of high similarity than those of low similarity. Transformed scores (log) to remove heterogeneity of variance gave a highly significant $F$ ($P < .001$). A comparison of Exp. 2H and 1.5H (again after transforming scores) shows the influence of rate of presentation on learning. The $F$ here was also highly significant ($P < .001$) demonstrating that increasing the rate of presentation from 2 sec. to 1.5 sec. made the task a more difficult one when measured in mean number of trials to learn.

The influence of intertrial interval on learning is negligible for all three experiments. The $F$ for this variable does not approach significance for either Exp. 2L or 2H. For Exp. 1.5H the faster learning by distributed practice as seen in Table 1 just reaches the 5% confidence level.

We have not considered the problem of equivalence of learning ability of the groups in making the above comparisons. The *S*s of Exp. 2L and 2H were matched in learning the common practice list. However, since the practice list was presented at a 1.5-sec. rate in Exp. 1.5H, scores from this list could not be used for matching purposes. Furthermore, it is a fact that we lost more *S*s because of inability to learn in Exp. 1.5H than in Exp. 2H. These losses occurred

TABLE 1

Mean Trials to Learn and Relearn, and Mean Items Recalled

| | Exp. | 4 Sec. | 30 Sec. | 60 Sec. | $\sigma_m$* |
|---|---|---|---|---|---|
| Learn | 2L | 11.89 | 11.64 | 11.19 | .90 |
| | 2H | 18.86 | 17.06 | 19.05 | 1.82 |
| | 1.5H | 30.08 | 28.80 | 24.14 | 2.69 |
| Recall | 2L | 10.80 | 11.11 | 11.03 | .25 |
| | 2H | 12.00 | 11.28 | 12.00 | .23 |
| | 1.5H | 11.80 | 11.33 | 11.33 | .29 |
| Relearn | 2L | 3.92 | 3.78 | 4.06 | .36 |
| | 2H | 4.58 | 6.72 | 6.61 | .89 |
| | 1.5H | 6.33 | 7.72 | 6.80 | 1.12 |

* Estimated from between-*S*s error term for each experiment.

almost exclusively on the conditions of distributed practice. The implication of this selection is twofold. First, the differences in learning as a function of rate of presentation are probably underestimated because of the higher ability level of *S*s in Exp. 1.5H than in 2H. The second implication is that the meager facilitation produced by distributed practice in Exp. 1.5H probably results from the selection of *S*s who learn somewhat better under distributed conditions than under massed conditions. We have discussed this problem elsewhere (**7**). The conclusion from these considerations is that the barely significant facilitation shown by distributed practice in Exp. 1.5H probably results from the selection of *S*s and would not have occurred if the sample were comparable to those in the other two experiments. In connection with this point it may be mentioned that we initiated an experiment with the high-similarity lists using a 1:1-sec. rate of presentation. The attrition of *S*s was so great because of the difficulty of the task that we discontinued it. For the *S*s which were completed ($N = 13$), however, we found no evidence of any greater facilitation in distributed practice than shown in Exp. 1.5H. We are strongly inclined to conclude, therefore, that increased rate of presentation of verbal-discrimination lists does not increase the likelihood of facilitation in learning by distributed practice.

It was mentioned earlier that when intralist similarity is varied it is reciprocally related to interlist similarity when *S* serves in a series of conditions as in the present experiments. Practice effects in learning were significant for all three experiments, and while there was a trend in the data for these effects to be less for Exp. 2L (where interlist similarity would be high) than in Exp. 2H (where interlist similarity would be lower), the interaction between intralist similarity and practice was far from significant.

*Recall.*—The recall scores in Table 1 show no appreciable differences as a function of intertrial rest. Since intertrial rest did not influence learning to any extent, we have no problem of adjusting for differences in rate of acquisition. We may conclude with confidence that intertrial interval does not influence retention as measured by recall.

When we turn to intralist similarity, however, significant differences in recall are obtained. A comparison of the raw recall scores for Exp. 2L vs. Exp. 2H gives a highly significant *F*, with the items in the high-similarity lists being better recalled. The recall does not vary as a function of rate of presentation (Exp. 2H vs. Exp. 1.5H). We have shown elsewhere (**8**) that comparison of raw recall scores is inappropriate when material has been learned at different rates to the same criterion. We also presented a solution to this problem which we called a successive probability analysis. The analysis adjusts for differences in acquisition rates and compares items at recall which were of equal strength at end of learning. Such a comparison is given in Fig. 1. A statistical test of the differences in these adjusted scores (as discussed elsewhere, **3, 11**) shows the difference between Exp. 2L and 2H to be significant far beyond the 1% level of confidence.

Again the question may be raised as to whether or not the difference in recall as a function of intralist similarity results from the reciprocal relationships between intralist and interlist similarity. It might be supposed that the superior recall of the high-similarity lists results from the fact that recall is interfered with less from previously learned lists than is recall of the low-similarity lists. An examination of recall as a function of stage of practice shows that at all stages recall of the high-similarity lists is superior. Recall of the low-similarity lists decreased slightly from a mean of 11.33 for the first experimental list to 10.78 for the third. The recall of the high-similarity lists remained about constant, being 11.75 on the first experimental list and 11.70 on the third. Even this small difference in recall as a function of stage of practice would probably disappear if adjusted for small differences in rate of learning as a function of stage of practice as discussed earlier. The conclusion is that the observed differences in recall are a function of intralist similarity with little if any confounding by interlist similarity.

There is still another question that might be raised about the recall scores. It might be suggested that recall in Exp. 1.5H is as high as in Exp. 2H because of the higher ability level of *S*s. That is, any decrease in recall that might be

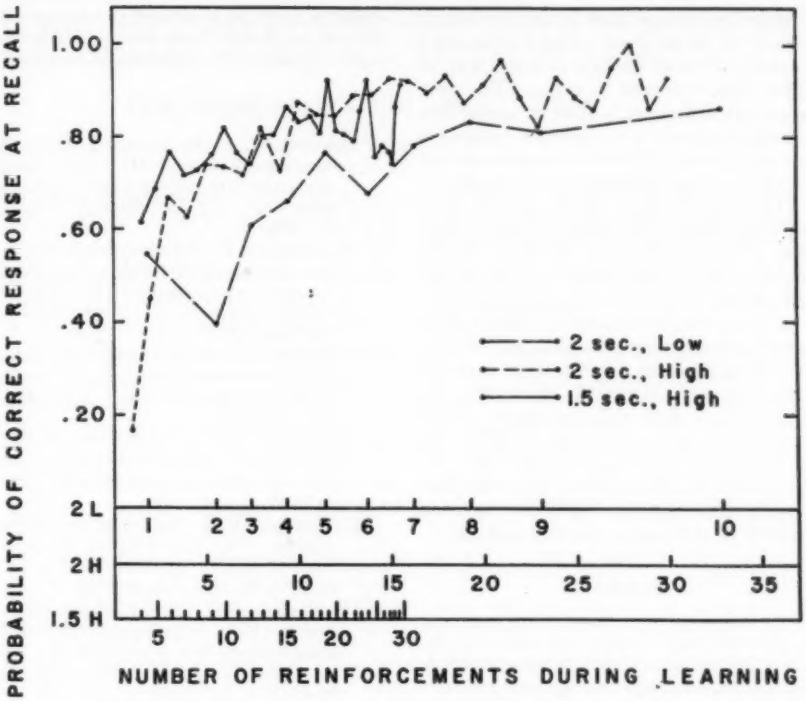


FIG. 1. Probability of correct response at recall as a function of rate of presentation and intralist similarity after groups had been equated for associative strength of items at end of learning using a successive probability analysis.

caused by the more rapid rate of presentation would be compensated for by the higher ability level of *Ss*. For each experiment we have made a comparison of recall as a function of learning ability (18 fast-learning *Ss* vs. 18 slow-learning *Ss*) and have found no difference. This confirms a previous report (8) on recall of serial lists as a function of ability level and denies the possibility that the present recall results can be attributed to differences in learning ability of *Ss*.

*Relearning.*—The relearning scores in Table 1 show the ordering of difficulty to be the same as during learning. Thus, as regards intralist similarity, although fewer items were lost from the high-similarity lists than from the low as measured by recall, it took appreciably longer to relearn them.

## DISCUSSION

There are two findings to be discussed briefly. First, it is noted that under extreme task difficulty we have found no facilitation in learning by distributed practice. In verbal discrimination, unlike serial and paired-associate learning, *S* responds to every presentation of words. It would seem, therefore, that explanations of the effects of distributed practice based only on a response-produced form of inhibition would find some difficulty with these results. Certainly we would have expected inhibition of such type to have been present in Exp. 1.5H where the rate of presentation (hence response) was about as fast as can be practically given. Increased speed of presentation has been found to interact with intertrial interval in both paired-associate (2) and serial learning (1) so that the faster the rate of presentation the greater the facilitation by distributed practice. This relationship does not seem to hold for verbal-discrimination learning. If a simple inhibition theory

(regardless of how such inhibition is produced) is to be used as an explanatory concept, it must be tied in some way to differences involved in tasks. The only apparent difference is that in verbal discrimination only a recognition process is involved whereas in paired-associate and serial learning anticipation is required.

The results have shown that lists of high similarity are better recalled than lists of low similarity. In none of the experiments in this series have we found lists of low similarity to be recalled better than lists of high similarity. While these previous results may be clouded because of the reciprocal relationship between intertask and intratask similarity, we have shown that this argument is not appropriate for the present situation. It is quite possible, however, that the differences could be ascribed to interference produced by response tendencies learned outside of the experimental situation.

## Summary

Three separate experiments were conducted in which intralist similarity and rate of presentation were varied for verbal-discrimination lists. Two levels of similarity were used and two rates of presentation. Similarity was varied by using different frequencies of repetitions of consonants in constructing the 14-pairs list of consonant syllables. The two speeds of presentation were 2:2 sec., and 1.5:1.5 sec. Thirty-six *S*s served in each experiment for one practice and three experimental conditions. During each of the experimental sessions *S* learned with either a 4-, 30-, or 60-sec. intertrial interval. Retention of each list was taken after 24 hr.

The major findings were as follows:

1. Faster learning took place for lists of low similarity than for those of high similarity. The faster the presentation rate the slower the learning. Speed of learning was unaffected by intertrial interval.

2. Recall of the high-similarity lists was better than of the low, but was unrelated to ability level and rate of presentation. Retention as measured by relearning had the same relation to intralist similarity and rate of presentation as did the original learning.

The difficulty of interpreting the results in terms of a simple inhibition theory as has been applied to serial and paired-associate learning was discussed. The fact that lists of high similarity were better recalled than list of low similarity might be attributed to lower probability of interference from response tendencies acquired outside of the experimental situation.

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# THE RELATION OF APPARENT SHAPE TO APPARENT SLANT IN THE PERCEPTION OF OBJECTS[1]

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The problem of how we perceive the shape of an object in space is complicated by the optical fact that to a particular retinal form there does not correspond a unique physical form but a whole set of possible physical forms. A given sheaf of light rays whose cross section is a particular form may be reflected from any surface whose margins coincide with the margins of the sheaf of rays; the surface does not have to be perpendicular but may be inclined to the sheaf. This set of surfaces is, mathematically, the family of perspective transformations of the cross section. A square cross section, for example, may arise from a family of variously inclined trapezoids. A trapezoidal cross section may arise not only from an inclined square but also from a different family of inclined trapezoids, of which the square is only a special case.

The optical fact seems to contradict the possibility of a correspondence between variations of the retinal image (the proximal stimulus) and variations of the object (the distal stimulus). Consequently it makes it impossible to assume any simple correspondence between the retinal image and a true perception of form. How, then, *do* we get an objective perception of form?

*The hypothesis of a psychological invariant.*—One kind of answer is to suppose that men have hypothetical sensations of form, each of which is in correspondence with the cross section of a particular sheaf of rays, and then to suppose that a sensation of form is *corrected* by past experience with the object in question. The difficulties with this answer have often been pointed out and need not be reviewed here. A more sophisticated answer is to suppose that we get a perception of the *inclination* of the form along with the sensation of the form as such, and then to suppose that these two experiences are related as mutually dependent processes—that they are, in Koffka's words, "linked together" (**9**, p. 229). This is a very appealing hypothesis to explain constancy. If it is true that an impression of shape is never obtained without a concomitant impression of slant, then it is possible that these two impressions may interact psychologically (or physiologically). If the interaction is precise, there could arise a final perception which, like the ratio (or the sum or the product) of two variable quantities, is constant. This constant product of two variable impressions might be the basis of our objectively correct perceptions of shape.

The hypothesis that impressions of

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shape and slant are coupled psychologically is implied by Helmholtz (**6,** p. 15) and is explicitly stated by Koffka (**9,** p. 229). It is closely related to the hypothesis that impressions of the *size and distance* of an object are coupled psychologically, which has an even larger literature. This has been frequently stated and studied by Boring and has recently been reviewed by Kilpatrick and Ittelson (**8**), who have a neat formula for what they call the size-distance invariance hypothesis, namely: *a retinal projection of given size determines a unique ratio of apparent size to apparent distance.* This formula can well be applied equally to shape: *a retinal projection of a given form determines a unique relation of apparent shape to apparent slant.* This is the explicit hypothesis with which we are concerned.

*The hypothesis of optical stimulus variables for the slant of a surface.*—A flat object seen under ordinary conditions always has edges and usually has a textured surface. The form of the edges and the nature of the texture are projected in the retinal images of two eyes. When the surface is inclined to the line of sight, the images manifest a compression of both form and texture (**3,** p. 172), and also a skew of form and texture in one image relative to the other and a similar skew in each image during head movement. These three types of compression and skew are concomitant, and are proportional to the optical slant of the surface. Conceivably they are stimuli for the impression of optical slant. Conceivably they are also stimuli for the impression of *shape* if we are willing to assume that the form and the texture of a surface are not separable but are closely interrelated. This possibility suggests a quite different explanation for the constancy of shape perception, namely, that it is based on constant properties of optical stimulation.

It should be noted that the compression of the texture can be eliminated from each retinal image by presenting an object with a homogeneous surface, and that the two types of skew of both form and texture can be eliminated by requiring monocular vision and a motionless head. The stimulus array is thereby reduced to the form of the edges alone. The resulting percept is a sort of disembodied form—the merest ghost of a substantial object (**4**). Nevertheless, this is the kind of form presupposed in current theories of constancy—textureless, single, and static. It is the "apparent shape" referred to in the formula above. It is possible, however, that the kind of form which shows constancy is textured, disparate, and mobile.

*The implications of the hypothesis of a shape-slant invariant.*—The formula should be examined for what it does and does not imply, with a view to experiments. It asserts first that a retinal form determines a family of possible apparent shapes, and second that each of these apparent shapes is linked with a corresponding apparent slant. An implication of the first assertion is that this reduced stimulus does *not* determine a single phenomenal shape, or a "sensation" of shape. It contradicts the commonly accepted view that, when the cues for depth are absent, the perceived shape of an object is determined by the shape of the retinal image. Boring, for instance, has expressed the opinion that perceived size depends on retinal size under reduction conditions (**2, 7**), and presumably the same rule is supposed to hold for shape. The formula seems to imply that there is no such thing as a retinal stimulus for shape, but only a stimulus for a family of shapes. Here is a clear-cut experimental issue:

Does or does not phenomenal shape become variable and indeterminate when the stimulus is a retinal contour form?

It should also be noted that the formula does not say anything explicit about what the apparent shape will be when the apparent slant is determined, i.e., when the cues for depth are present. It applies to the "pure" form obtained when the cues are absent. It states that an impression of shape under the latter conditions will vary inversely with the accompanying impression of slant; that the two impressions will covary in the manner necessary to satisfy the invariant relation. If an impression of slant is somehow aroused, the apparent shape must be that of an object which would yield the current retinal image; if an impression of shape is somehow aroused, the apparent slant must be that physical slant which would yield the retinal image. This implication of the formula can also be tested experimentally. An extra hypothesis is required to account for the arousal of an impression of slant or shape: the readiest explanation would be that an assumption, attitude, or expectation determines it. In the absence of sensory information the organism presumes a slant or a shape for the object. A presumptive slant would be the frontal plane, or perhaps a slant which conforms to that of the background surface on which the object stands. A presumptive shape would be the circle within its family of ellipses, or a rectangle in the family of trapezoids.

The formula says nothing about shape perception when cues for slant are present. Since this is the condition under which shape constancy occurs, it is not in itself an explanation of constancy. Nevertheless it seems to be consistent with such facts; perhaps it is a consequence or corollary of constancy which becomes manifest only when the cues for slant are absent. The supplementary theory for the case when the cues are present might belong to either of the following types:

A follower of Helmholtz (6) would argue that the organism discovers in the course of time that the cues for the slant of an object vary concomitantly with the retinal projected form of the object. Only then is he in a position to infer the true shape of the object from the retinal shape by combining this information with the cues for slant. The psychological linkage between impressions of shape and slant would arise as the result of associations between them.

A psychophysical theory, on the other hand, would argue that if the concomitant variation referred to is a discoverable fact it must be an invariant of stimulation itself. The compression-and-skew of the dual retinal images, already referred to, is a high-order variable of stimulation which reflects both the slant and the shape of the physical object. This stimulus invariant is a matter of optics and geometry, not of psychology, and it might prove to be the cause of a simple and immediate experience of shape-at-a-slant. The psychological linkage between impressions of shape and slant, if verifiable, would be manifest only when the stimulus invariant had been eliminated in the retinal images, leaving only bare contours and form. In this event, associative processes could be expected to occur and perhaps also the semi-intellectual processes of assumption, expectation, and inference described by Helmholtz.

The experiments to be reported are tests of the shape-slant invariance formula and its implications. They cannot be expected to decide between alternative theories of shape constancy but they may clarify the factual background for the theories.

## Experiment I

The question is whether apparent shape is linked with apparent slant when the latter is not determined by stimulation. Although experiments by Thouless (12) and by Eissler (9, p. 229) are relevant to the question in a general way, only one study exists which set out specifically to test the hypothesis, that of Stavrianos (11). She had her *O*s make explicit judg-

ments of the shape and the slant of an inclined rectangle, separately, under three conditions of observation: (*a*) full binocular vision, (*b*) binocular vision with reduction tubes, and (*c*) monocular vision with a reduction tube. She found that the progressive elimination of stimuli for slant caused the judgments of slant to become more variable and less accurate, but not the judgments of shape. The latter did not deteriorate correspondingly and the error of seen shape did not vary as a strict function of the error of seen slant, as the hypothesis demands. The judgments of shape and of slant, however, had been made successively and separately, and this fact might explain the failure to verify the hypothesis. Two other experiments were therefore run in which an attempt was made to force *O* to take a "shape-and-slant" attitude during both judgments. In both, a precise relation between errors of shape and slant failed to appear in the data, although they did justify the conclusion that "perception of shape may be roughly related to explicit judgments of inclination." A crucial test of the hypothesis probably requires an experiment in which the judgments of shape and slant are not explicit, but are implicit in the same act of matching the standard object.[2]

Another purpose of the present experiment was to discover whether, in the absence of stimuli for slant, the retinal shape determines only a family of possible perceived shapes or whether it determines the perception of a single shape in the frontal plane.

*Apparatus and procedure.*—The plan of the experiment was to present *O* with a standard object suspended in darkness and have him match it for both shape and slant with one of a series of comparison objects in the light which systematically varied in shape and slant. The standard object was viewed with monocular vision and a motionless head, the comparison objects with binocular vision and a mobile head. The standard object was a luminous shape cut out of cardboard over a sheet of textureless ground glass in a light box. The latter was set at 89 in. from the eye and could be rotated on a horizontal axis. The comparison objects were a set of sheet-metal shapes, painted white and mounted at different degrees of slant (or no slant) on a black background or panel. They were set at approximately 30 in. from the eyes and were one-third the size of the standard object.

The experiment was run with two kinds of standard objects to be matched, quadrilaterals and triangles. The former included a rectangle but the latter did not include an equilateral triangle, all triangles being flatter than equilateral. The former included a "normal" shape; the latter did not.

On half the trials *O* was presented with a physically slanted 10- by 8-in. rectangle, and on the other half with a physically frontal trapezoid equivalent to the cross section of the light rays from the rectangle. (The latter will be referred to as the "cross-sectional" trapezoid.) These two physically different but optically equivalent objects yielded the same distribution of judgments; hence we may conclude that they were indistinguishable, and that stimulation for slant had been effectively eliminated in viewing the standard. A similar procedure was used for the triangles, with the same outcome. The standard slanted triangle was of 10-in. base and 8-in. altitude.

When the rectangle was presented, the face of the light box was inclined either floorwise or ceilingwise (top backward or top forward) at three angles of inclination, 30°, 45°, and 60°. Corresponding to these six stimuli were six frontal trapezoids, half with sides converging upward and half converging downward, at three degrees of vertical compression. Each *O* was thus given 12 presentations. Including the triangles he made, in all, 24 matches or judgments of shape-and-slant. There were 30 *O*s in the experiment.

The standard stimulus in this experiment was, in effect, a sheaf of light rays and there were 12 different ray sheaves employed, six being quadrilateral in cross section and six being triangular. For each of these 12 stimuli a set of comparison stimuli was prepared. These, it will be recalled, were shapes mounted at various slants on a panel. Consider, for example, the ray sheaf illustrated in Fig. 1. Its cross section is a flattened trape-

[2] Another test of the hypothesis has been noted since this paper was written, by J. Langdon (**10**). With a quite different experiment, Langdon also failed to get the sort of results which Koffka believed should follow from the invariant relationship.

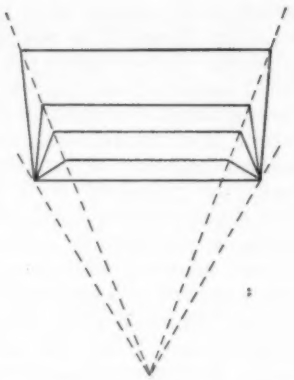

FIG. 1. Schematic view looking down on the sheaf of rays from a rectangle at a 60° inclination floorwise. Equivalent trapezoids are indicated at lesser inclinations, and one at zero inclination. The shapes constitute a "transformation series." In the experiment there were six such series and, from each, *O* was shown two standard objects, both the inclined rectangle and the frontal trapezoid.

zoid. The *O* might perceive a rectangle with a top slanted backward 60°, or either of two trapezoids with tops slanted at lesser amounts, or a still more flattened trapezoid on the frontal plane. This group of quadrilaterals will be called a "transformation series." The set of comparison objects for each stimulus had to include a number of shape-and-slant combinations which were *within* the relevant transformation series and also some which were *outside* the series in order to test the hypothesis of an invariant. The latter combinations, if chosen by *O*, would go counter to the hypothesis. The combinations included the cases for which an invariant relation would be most likely to fail.

The appropriate set of comparison objects was mounted on *O*'s right on a panel illuminated by a low-wattage red lamp. It included from two to four choices which would be consistent with the invariant relation (depending on the degree of slant of the standard) and two choices counter to the invariant.

Each *O* was seated in the darkroom in front of a screen with an aperture for monocular vision and a biting board. He was shown the comparison objects and was told that they were similar to (but not the same as) the objects he would see through the aperture. He was instructed about the aperture and told that when the shutter was raised he would see a luminous figure at some distance. He was to note both its shape and its slant (since it might be either frontal to his eye or inclined) and then turn to the panel and match it for shape and slant. He should check his match once, and would be allowed a third look through the aperture if still uncertain. Each presentation of the standard was for 10 sec. but there was no time limit for inspecting the comparisons. The 24 matches made by each *O* were in random order for the various experimental conditions.

TABLE 1

DISTRIBUTION OF JUDGMENTS AMONG SIX COMPARISON OBJECTS IN THE QUADRILATERAL GROUP

| Objects Within Transformation Series | | Objects Outside of Transformation Series | |
|---|---|---|---|
| Judgments | No. | Judgments | No. |
| 1. Rectangle slanted | 34 | 5. Rectangle in frontal plane | 0 |
| 2. Cross-sectional trap. in frontal plane | 197 | 6. Cross-sectional trap. slanted | 64 |
| 3. Intermediate trap. at 15° | 61 | | |
| 4. Intermediate trap. at 30° | 4 | | |
| Total number of judgments within the transformation series | 296 | Total number of judgments outside of the transformation series | 64 |

*Results.*—The questions posed are these. Will the matches be variable within the family of projectively equivalent shapes, or not variable? Will they occur wholly within the family or not? Table 1, representing the quadrilateral stimuli, shows that

TABLE 2

DISTRIBUTION OF JUDGMENTS AMONG SIX COMPARISON OBJECTS IN THE TRIANGLE GROUP

| Within Invariant | | Counter to Invariant | |
|---|---|---|---|
| Judgments | No. | Judgments | No. |
| 1. Standard triangle slanted | 24 | 5. Standard triangle in frontal plane | 0 |
| 2. Cross-sectional triangle in frontal plane | 279 | 6. Cross-sectional triangle slanted | 28 |
| 3. Intermediate triangle at 15° | 26 | | |
| 4. Intermediate triangle at 30° | 3 | | |
| Total number of judgments within the transformation series | 332 | Total number of judgments outside of the transformation series | 28 |

the phenomenal shapes perceived were variable. No single perception of form was determined under these reduced stimulus conditions, although the perception of a frontal plane form is predominant. The case is similar for the triangular stimuli in Table 2. The results support the hypothesis that phenomenal shape becomes indeterminate when phenomenal slant is made indeterminate, not the classical view that retinal shape determines phenomenal shape when not interfered with. Doubt is cast on the theory of a "form sense" and on the possibility of reducing perceptions of objects to sensations of form.

In answer to the second question, the tables show 64 and 28 matches, respectively, out of a possible 360 (12 matches for 30 *O*s) which are exceptions to the shape-slant invariance formula. We must conclude that the hypothetical linkage between psychological shape and slant is not rigid. It cannot be asserted that a retinal projection of a given form determines a unique relation of apparent shape to apparent slant but only that there is a tendency to such a relation. The results are analogous to those of Stavrianos (**10**).

The number of exceptions is greater for the quadrilateral than for the triangular stimuli by 10% ($CR = 4.08$, $P = .01$). Moreover the number of exceptions, with both quadrilaterals and triangles, is greater for ceilingwise slant than it is for floorwise slant ($CR = 3.08$ and 3.20, respectively; $P = .01$). These significant differences suggest that the strength of the connections between impressions of shape and slant depends on the kind of shape investigated and on the direction of its slant. They are consistent with the view that the connections may be learned.

There is apparently a strong presumption to see a shape in the frontal plane, even though it is not wholly determining. In both tables the cross-sectional shape is more frequent than all the equivalent slanted shapes taken together. The frontal slant can be considered normal or statistically probable, or conceived as a stable structure in the style of gestalt theory. Similarly a rectangle is normal or stable as compared with trapezoids, but the standard triangle presented is not so as compared with the other triangles in the series. A possible tendency, however, to perceive the rectangle more frequently than the standard triangle (34 and 24 matches, respectively) is not confirmed, since the difference is not significant ($P > .10$). Comparing the slanted rectangle with the frontal trapezoid in Table 1, both percepts being equally possible, it is evident that the presumption of frontal position wins out in a striking way over the presumption of rectangular shape. Neither a statistical "best bet" theory nor a theory of stable structures provides any ready explanation of the strength of these presumptions, taking the results together. It should be noted that the most probable (or stable) percept of all, the rectangle in the frontal plane, was not once obtained in the whole 360 judgments. It is not clear, however, why this should be so.

## Experiment II

A different method of testing a consequence of the slant-shape invariance formula was next conceived and tried out. This did not depend on judgments of a luminous shape in the dark but on judgments of a shape against a visible background. The method was based on the expectation that a flat shape of homogeneous color will, when slanted away from a visible textured

background, assume the slant of its background if binocular disparity and motion perspective are eliminated from stimulation (**3**, p. 178).

*Method.*—An isosceles triangle cut out of white cardboard was mounted on a large vertical screen of black painted plasterboard at a 45° angle of slant outward from the base of the triangle. This was the standard object. It had to be matched with one of two comparison triangles mounted flat on the background, one above and to its left, the other below and to its right. One of these had the same shape as the standard while the other had the shape the standard would have if projected on the background. If the background induces a presumptive error in the impression of slant, this should determine a corresponding error in the impression of shape and *O* will match the standard with the latter instead of the former. The question is, will a presumptive slant induced by the stimulus situation determine a false judgment of shape?

Three different standard triangles were used, all with 10-in. bases but with altitudes of 8.75, 6.75, and 5 in. They will be referred to as $S_1$, $S_2$, and $S_3$, respectively. A set of comparison triangles was prepared, also with 10-in. base but with altitudes of 8.75, 6.75, 5, and 3.5 in. They will be referred to as $C_1$, $C_2$, $C_3$, and $C_4$. A standard and comparison triangle with the same index number are equal in shape (and size). A standard triangle at a 45° slant is projectively equivalent to the comparison triangle with the next larger index number (approximately).

Each *O* made three matches of the three standards. He observed the standard and its two comparison objects on their common background through a monocular aperture at a distance of 7 ft. The shadow cast by the slanted standard was made invisible by illuminating the objects solely with a circular fluorescent lamp mounted on the far side of the aperture screen and centered on the aperture through which the objects were viewed. Thirty naive *O*s were used. Each was seated in the darkroom and told that when he applied his eye to the peephole in the screen before him, he would see three triangles mounted on the wall in a diagonal line. He was to judge whether the middle triangle was the same as the one above or the one below it.

*Results.*—All *O*s reported seeing the standard triangle as flat against the wall. The effect was compelling and no *O* voiced any doubt about it. Table 3 shows the results of the experiment, along with those of the next experiment in which binocular vision was introduced. The left side of the table indicates that all 30 *O*s matched the standard with the comparison whose shape was its projection, not with the comparison whose shape was objectively the same. $S_1$ was matched with $C_2$, $S_2$ with $C_3$, and $S_3$ with $C_4$.

TABLE 3

COMPARISON TRIANGLES $C_1$, $C_2$, AND $C_3$ WHICH WERE IDENTIFIED AS EQUAL TO STANDARD TRIANGLES $S_1$, $S_2$, AND $S_3$

| | Monocular Vision (Exp. II) | | | Binocular Vision (Exp. III) | | |
|---|---|---|---|---|---|---|
| Triangle Presented / Expected Results | $S_1$ / $C_2$ | $S_2$ / $C_3$ | $S_3$ / $C_4$ | $S_1$ / $C_1$ | $S_2$ / $C_2$ | $S_3$ / $C_3$ |
| No. of deviations | 0 | 0 | 0 | 9 | 7 | 7 |
| No. as expected | 30 | 30 | 30 | 21 | 23 | 23 |
| Per cent as expected | 100 | 100 | 100 | 70 | 77 | 77 |

An illusory impression of slant, therefore, goes with a corresponding illusion in the perception of shape, under these conditions. But it may be noted that this experiment is a much less exacting test for the unique linkage hypothesis than the last. It does not show that each of a large number of possible apparent shapes is linked with one of a large number of apparent slants. The method employed, however, could be used in more elaborate experiments and errors could be measured with more precision. The background used was perpendicular to the line of sight and the slant induced on the standard form was frontal. The effect on slant of using a background itself at a slant is not certain. Preliminary experiments suggest that the effect still holds and that illusions of shape can be induced, but the degree of linkage has not been measured.

## Experiment III

In the preceding experiments stimulation for the slant of the standard object was eliminated. Constancy of shape probably depends on the presence of such stimulation. The last experiment can be modified to permit it by simply converting the monocular aperture into a binocular slit.

*Method.*—The *O* sees the standard and its two comparisons, as before, but now the middle triangle appears to slant forward from the background. Its edges are increasingly uncrossed disparate from the base to the apex (or decreasingly crossed disparate) and they manifest a slight skew when the head is not held motionless. The texture perspective of its surface, however, is probably invisible since the latter is smooth white cardboard at 7 ft. If the slant of the object is correctly seen, the shape should also be correctly seen. The *O* should then match the standard with the comparison object whose shape is objectively the same, not the one whose shape is projectively the same. In terms of the index numbers, $S_1$ should be matched with $C_1$, $S_2$ with $C_2$, and $S_3$ with $C_3$. The same group of 30 *O*s was used, the binocular matches of this experiment following the monocular ones of the previous experiment. The instructions were the same as before: to judge whether the middle triangle was the same as the one above or below.

*Results.*—The right side of Table 3 shows that not all 30 *O*s made the predicted matches. Nine *O*s matched the tallest triangle ($S_1$) with the just shorter one ($C_2$), and 7 *O*s matched the shorter triangles with ones just shorter than themselves ($S_2$ with $C_3$, and $S_3$ with $C_4$). In general, however, there was a tendency toward constancy of shape. The expected matches predominate.

It cannot be argued that the *O*s who failed to attain constancy did so because they failed to see the slant of the standard triangle. Several of these *O*s were asked immediately to reproduce this slant kinesthetically by the method of adjusting a vertical plate, hinged in the middle, with the palm of the hand; they could do so with some accuracy. We must evidently conclude that constancy was imperfect or incomplete in this experiment, an outcome not unusual in experiments of this sort. Why this is so is still unclear.

## Discussion

It has been widely assumed that we perceive the shape of an object in space on the basis of two separate variable impressions, apparent shape and apparent slant. The relation of these phenomenal variables to stimulation and to each other is a difficult and puzzling problem. Their relation to each other under reduced stimulation is the part of the problem most amenable to experimentation. The present experiments are principally of this sort.

The results of these experiments are not conclusive for a theory of constancy, and not even notably consistent with one another. They do cast doubt, however, on the distinction between apparent form as a sensation and apparent slant as a perception. The experimental methods employed, moreover, are promising, and further use of them may prove illuminating. There is a question whether such procedures with reduced stimulation will ever solve the general problem of the perception of objects in the environment. Perhaps the perception of objects is *not* based on two separate phenomenal variables, shape and slant. If the seeing of the boundaries and the texture of a surface are not distinct phenomena but are instead closely related, the question of shape constancy may be included in the question of slant perception. This seems to the writers the most promising line for future research.

## Summary

The relationship of apparent shape and apparent slant to the perception of the shape of objects in space was studied in three experiments. It was demonstrated in Exp. I that a reduced retinal shape without stimulation for the slant of the surface can induce a whole family of apparent shapes and does not necessarily determine the perpendicular cross-sectional member of the

family. But there was a strong "presumption" for the frontal shape and, in the quadrilateral family, this won out over the tendency to see a rectangle. As to the linkage between shape and slant within the family of shape-slants, it proved to be by no means perfect. Experiment II showed that, again for a reduced retinal shape, an illusory slant can induce an illusory shape. The phenomenal slant of such an object will tend to be that of the textured background surface, whatever its physical slant may be. Experiment II yielded no exceptions to the linkage hypothesis, but it did not constitute as strict a test. The strictness of the linkage seemed to depend on the kind of shape seen and on the direction of its slant. The linkage may be learned, but a probabalistic theory of the percepts attained does not readily explain the facts. Experiment III showed that constancy of the perceptions of shape appeared when stimulation for slant was provided, but not universally.

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# DARK-ADAPTATION LUMINANCE THRESHOLDS FOR THE RESOLUTION OF DETAIL FOLLOWING DIFFERENT DURATIONS OF LIGHT ADAPTATION [1]

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The progress of dark adaptation of the eye depends to a marked extent upon the initial stage of light adaptation. The variation of either the luminance of the preadapting light or the duration of the pre-exposure affects the course of the subsequent increase in sensitivity during a stay in the dark. This adaptation process is ordinarily traced by determining the luminance threshold, the lowest luminance of light which can be detected, at various intervals of time until it has reached a fairly stable level. In general, measurements of the eye as a whole show a primary rapid drop in threshold which proceeds for over 30 min. The early part of the curve corresponds to cone adaptation; the secondary decline is a function of the rods.

Various studies (**3, 6, 7, 8, 9**) show that duration and luminance of pre-exposure generally have certain similar effects upon the shape of the luminance threshold curve. It is a question, however, whether the luminance of the pre-exposure light and the duration of the pre-exposure have identical effects upon the course of dark adaptation. A chemical formulation of the visual cycle proposed by Wald and Clark (**8**) predicts that recovery of the rods from short intense flashes of light will be faster than recovery from prolonged exposures to lower luminances. This prediction was supported by their data. Following the short duration and high luminance, the rod adaptation curve was so rapid that it overtook and crossed the long-duration, low-luminance curve. Recent experiments have sought to furnish dark-adaptation data for preadaptation conditions under which the product of luminance and duration of pre-exposure was a constant. For the peripheral retina, Haig (**3**) found that an increase in the degree of light adaptation, whether produced by raising the luminance or by prolonging the exposure, affected subsequent rod dark adaptation in an identical manner.

In the fovea, Mote and Riopelle (**7**), using four preadapting luminances (11,300, 5,650, 1,130, and 565 ml.) and four durations (300, 150, 30, and 15 sec.), showed that the curves, in which the products of luminances and duration are equal, are the same for the two higher luminances and two longer durations, and also for the two lower luminances and two shorter durations. For other values the curves were generally not the same. Generally, the lower luminances, longer duration curves, had lower initial threshold values, steeper slopes, and reached a final steady threshold value sooner than did the curves for higher luminances and shorter durations.

Thus far we have considered the relation between dark adaptation and the previous light adaptation with reference to the luminance threshold for the detection of light. Besides the simple

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light detection threshold, other criteria of sensitivity during dark adaptation are of considerable interest. A question of undoubted practical importance is how visual acuity, or the capacity of the eye for the resolution of visual detail, increases during dark adaptation. We need to know whether different visual resolution criteria respond in the same way to changes in the condition of preadaptation.

Recent data, summarized by Brown (2), suggest that the dark-adaptation function is fairly independent of the particular criterion of threshold. Brown, Graham, Leibowitz, and Ranken (1) determined luminance thresholds for the resolution of grating test objects. Different degrees of visual resolution yielded similar results, with the cone sections of the curves parallel to those for light detection. In further extension of this research, Brown (2) studied the effect of varying the preadapting luminance upon the luminance threshold curves for different acuities. The three resulting dark-adaptation functions have the same characteristic shape as the curves for light detection.

Two effects of the level of visual acuity were noted. First, visual acuity is a parameter which determines the position of the curve on the log luminance threshold axis. The higher the degree of visual acuity, the higher the position of the curve. Second, curves for the finer gratings, representing higher acuities, drop to a final steady level after about 5 to 12 min. in the dark. Such curves characterize cone function. Only the coarser gratings will permit the characteristic rod portions of the dark-adaptation curves to appear.

Since in both experiments the course of dark adaptation for different acuities was determined following a constant duration of pre-exposure (5 min.), the results do not indicate what happens following pre-exposures of shorter or longer duration. The present experiment aims to remedy this lack by showing how luminance thresholds for the resolution of visual detail during dark adaptation vary as a function of preadapting duration.

Specifically, the present experiment is concerned with the following questions: (*a*) How does the luminance threshold for a given acuity level vary as a function of time in the dark, following different durations of pre-exposure? (*b*) What is the effect of level of visual acuity? (*c*) With respect to visual acuity criteria, does duration of pre-exposure influence the subsequent dark adaptation in the same way as luminance of pre-exposure? While the present experiment does not vary both luminance and duration of preadaptation, the results may be compared with those obtained by Brown (2) in a similar experiment on the course of dark adaptation for different visual acuity tasks as a function of pre-exposure luminance.

## Apparatus

The apparatus used is a modified Hecht-Shlaer adaptometer (6). Modifications enabling determination of acuity thresholds during dark adaptation are discussed in detail by Brown (2). Further modification in this experiment enabling determination of acuity thresholds, particularly during the early seconds of dark adaptation, are discussed in detail below.

The Hecht-Shlaer apparatus essentially involves two optical systems: The first is a light-adaptation system which presents a Maxwellian view of a 35° circular field to which *S* light adapts. Let us consider the optical path of this system from light source to exit pupil. The light source consists of a 100-w. tungsten-filament frosted bulb mounted behind a 22-mm. circular opening filled by flashed opal glass. This glass diffuses the light, which is then controlled in luminance by neutral-tint Wratten filters, and next collimated by a lens located at a focal distance of 12 cm. from the flashed opal glass. A second lens then focuses the parallel light to a point 6 cm. distant, where is located a 3-mm. exit pupil through which *S* sees a field of approximately 35° diameter (visual angle). A fixation point at the center of this field is provided by a small cross scratched in a piece of plain glass located between the two lenses.

The second system is used during dark adaptation. This system, with which *E* can mechanically replace the first, enables flash presentation of a 7.3° test field during the dark-adaptation

period. The light source, used in the first system, sends diffused light through a neutral Wratten wedge and balancer, a spring-loaded camera shutter (the shutter was set at a speed of .016 sec.), and neutral Wratten fixed filters, before being made parallel by the collimating lens. A circular field stop, 4.45 cm. in diameter placed in the path of the collimated beam, limits the test field to a visual angle of 7.3°. A second lens of 36-cm. focal length, focuses the beam at the 3-mm. exit pupil. Fixation is provided by a red cross reflected into the center of the visual field by a .007-in. thick piece of cover glass located between the Wratten filters and the collimating lens.

A chin rest, used in both systems, is so positioned as to hold *S*'s pupil directly in back of the 3-mm. exit pupil.

The modification enabling determination of acuity thresholds was made by Brown, Graham, Leibowitz, and Ranken (1), and is discussed by Brown (2). This involves two minor changes in the Hecht-Shlaer dark-adaptation system. First, a holder, into which gratings can be inserted, is mounted between the wedge and neutral Wratten filters at an optical distance of 57.2 cm. from the exit pupil. Secondly, the red fixation cross is adjusted so that its optical distance to the exit pupil is approximately 57.2 cm. Thus accommodation for the cross and grating is essentially the same.

The modification enabling determination of acuity thresholds during the early seconds of dark adaptation involves the addition of two mechanical timers and the system diagrammed in Fig. 1. This system enables accurate timing, down to an interval of 1 sec., of two periods: (*a*) the light-adaptation period; and (*b*) the period between the end of light adaptation and the first flash during dark adaptation. With regard to the light-adaptation period, during experimental procedure the system can be controlled either automatically or manually.

Automatic control works as follows (Fig. 1): Switch $S_2$ remains closed throughout automatic procedure. The *E* adjusts the optical system to that for light adaptation by moving lever $L_1$ located on the side of the apparatus. This also

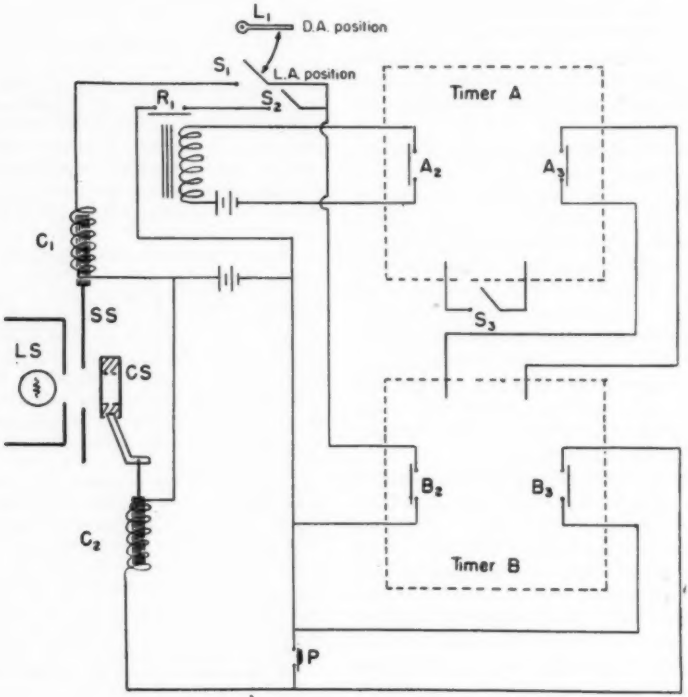


FIG. 1. Schema of timing circuit.

closes switch $S_1$. Solenoid $C_1$ is thus activated, and shutter *SS* is drawn upward cutting off the light from *LS*. Adjustment of lever $L_1$ also drops the camera shutter, *CS*, from the light path, although this is not shown in Fig. 1. Light adaptation is begun when *E* closes switch $S_3$ in the "starter" circuit of timer *A*. Contact $A_2$ closes immediately, relay $R_1$ opens, and shutter *SS* is released, exposing light source, *LS*. After a particular duration of light adaptation, as set on timer *A*, $A_2$ opens and shutter *SS* again cuts off the light from *LS*, ending light adaptation.

As soon as light adaptation ends, *E* moves $L_1$ so that the dark-adaptation system is thrown into position, and shutter *CS* is in the light path. (Moving the lever up also opens switch $S_1$, thus reopening shutter *SS*.) This shift to the dark-adaptation system has to be accomplished in less than 1 sec., since when light adaptation ends, contact $A_3$ closes, and timer *B* starts. One second thereafter $B_3$ closes and the camera shutter *CS* is tripped automatically. In this way, a test flash occurs precisely 1 sec. after light adaptation ends.

Manual control is used for light-adaptation periods of more than 2 min., which is the limit of both timers *A* and *B*. $S_3$ remains open throughout manual procedure. When the light-adaptation system is set in place, light starts timer *B* and closes shutter *SS* simultaneously. The *E* immediately replaces the light-adaptation system with the dark-adaptation system by shifting lever $L_1$. This has to be done in less than 1 sec. since shutter *CS* is tripped automatically 1 sec. after timer *B* starts.

The *E* presses push button, $P_1$ to present flashes after 1 sec. following light adaptation. This is done after either manual or automatic operation.

Calibration of the apparatus followed the same procedure described in detail by Brown (2). This involved four general considerations: (*a*) the luminance of the light-adapting field, (*b*) the luminance of the test (dark-adapting) field, (*c*) the visual angles subtended at the eye by the lines on the gratings, and (*d*) the densities of the neutral Wratten wedge and fixed filters.

The luminance of the light-adapting field was determined by a binocular luminance match with a standard field of equal area calibrated for luminance with the Macbeth Illuminometer. Its maximum was 14,800 ml. with the 100-w. bulb operated at 120 v.

The luminance of the test field was determined by a monocular luminance match using the comparison standard provided with the apparatus. The luminance of the standard field was calibrated with the Macbeth Illuminometer. By varying the wedge, *S* was able to match the two fields in luminance. The maximum luminance of the test field was thus determined to be 15,140 ml. when the 100-w. bulb was run at 120 v.

Three gratings, such as used by Brown (2), are used in the experiment. The grating lines are opaque and separated by transparent spaces of width equal to that of the lines. The visual angle subtended by the distance between the contours on these gratings was calculated from the known width of the lines, the magnification of the optical system, and the optical distance of the grating image from the eye. The visual acuities of the three gratings used were, respectively, .042, .083, and .62.

The filter densities were determined on a Martens photometer. The wedge density was checked by placing several different filters of known density in the filter holder and adjusting the wedge to obtain a match with the monocular matching device described above. The differences in settings of the wedge were then checked against the differences in density of the filters for which the settings were obtained.

## Method

The present experiment investigated threshold luminance for an acuity object as a function of time in dark after exposure to a 1000-ml. adapting field. Two parameters of this function also studied were: (*a*) duration of light adaptation (1 sec., 30 sec., 5 min., and 10 min.), and (*b*) the acuity value of the grating used in the test field (.042, .083, and .62). Since for the .083 acuity value there were no appreciable differences between the dark-adaptation curves following 5- and 10-min. light adaptation, the 10-min. duration was omitted for the two other acuity values[3]; this was done primarily in the interest of shortening the relatively lengthy procedure required in this experiment.

A modified psychophysical method of constant stimuli was used to determine the acuity thresholds during dark adaptation. For each point on the dark-adaptation curve, flashes of .016 sec. were presented to *S* with the grating randomly in positions 45° clockwise, 45° counterclockwise, or vertical. The *S* responded "right," "left," "vertical," or "no." For each point, from two to five responses were necessary such that at least one negative and one correct response were obtained. The threshold luminance at a point was then determined as the mean of the highest flash luminance at a "no" response and the lowest flash luminance at a correct re-

[3] Additional experiments involving the .62 acuity value showed no significant differences between dark-adaptation curves following 5-min. and 10-min. light-adaptation duration.

sponse. Incorrect responses were counted as "no" responses.

This method was used because the traditional constant-stimuli method would have required a prohibitive amount of time. The method of limits, used by Hecht (6), could not be used since threshold luminance for resolution of gratings is considerably higher than that for light detection; thus test flashes given at intervals of less than 10 sec. might have altered the course of dark adaptation.

Data were collected for two *S*s, one male, AD, and the other female, AG. Both observers had normal vision. The right eye of AD and the left eye of AG were used in all determinations.

The procedure during one experimental run involved a prelight-adaptation period, a light-adaptation period, and a dark-adaptation period.

During prelight adaptation, *S* sat in the darkroom until his visual sensitivity reached a constant minimum level. The *E* determined the constancy of sensitivity by presenting *S* every 2 min. with flashes of the test grating to be used, until the threshold luminance of the test flash was at a minimum and did not decrease by more than .2 log ml., over a period of 4 min. The *S* was then given a 15-sec. warning for light adaptation, at which time he positioned his head by means of the chin rest and looked through the 3-mm. exit pupil at the red fixation light. Another warning was given 5 sec. before light adaptation at the end of which time adaptation was begun.

The *E* began light adaptation in one of two ways: automatically or manually. On automatic, the light-adaptation system was thrown in (lever $L_1$ thrown down) just before the 15-sec. warning. Then *E* had to close $S_3$ for light adaptation to begin. On manual, the light-adaptation system was thrown in at the end of the 15-sec. warning at which time light adaptation began.

During the first minute of dark adaptation, flashes were given at 1, 15, 30, 45, and 60 sec. In a check experiment, it was found that reduction of the interval between flashes to as little as 10 sec. did not systematically or appreciably change the shape of the dark-adaptation curve. A 15-sec. flash interval was used, therefore, during the first minute. Flashes were then presented every minute, or every other minute, until the dark-adaptation curve reached a relatively constant minimum level, or until 30 min. had passed. The level of the dark-adaptation curve was assumed to be relatively constant when the threshold luminance did not change by more than .2 log ml. over a period of 4 min., and the level was assumed to be at a minimum when the curve was either at the cone leveling-off portion or the rod leveling-off portion, depending upon the particular grating used. For example, according to data collected by Brown, Graham, Leibowitz, and Ranken (1), the .62 acuity dark-adaptation curve reaches a minimum threshold at the cone leveling-off portion of the curve; our .62 acuity curves were thus ended along the cone level. These criteria, concerning a constant minimum level, depend primarily upon determinations, made by the above authors, of the appearance of the rod-cone break in the dark-adaptation curve, which determinations are substantiated by Brown (2). These criteria are thus felt to be justified, especially in view of the time gained in experimentation.

It was also found convenient, for the second and succeeding minutes, to present flashes 30 and 15 sec. before the minute. This provided information enabling *E* to obtain a more accurate bracket, between a correct and a negative response, for each minute.

It was found that for the short light-adaptation durations, up to three or four runs could be obtained in one experimental session. That is, each experimental point was determined by from two to five flashes, which meant that from two

TABLE 1

LOG THRESHOLD LUMINANCE IN MILLILAMBERTS DURING DARK ADAPTATION AFTER DIFFERENT DURATIONS OF LIGHT ADAPTATION

(Visual acuity = 0.042. *S*s AD and AG)

| Time in Dark (min.) | Duration of Light Adaptation | | | | | |
|---|---|---|---|---|---|---|
| | 1 Sec. | | 30 Sec. | | 5 Min. | |
| | AD | AG | AD | AG | AD | AG |
| 0.017 | −0.60 | −0.60 | −0.45 | −0.30 | 0.24 | 0.79 |
| 0.25 | −1.48 | −1.50 | −0.85 | −0.90 | 0.14 | 0.14 |
| 0.50 | −1.66 | −1.55 | −1.00 | −1.05 | −0.16 | 0.11 |
| 0.75 | −2.01 | −1.75 | −1.25 | −1.25 | −0.36 | −0.21 |
| 1 | −2.06 | −1.85 | −1.20 | −1.35 | −0.56 | −0.56 |
| 2 | −2.21 | −2.21 | −1.41 | −1.61 | −1.00 | −0.90 |
| 3 | −2.31 | −2.41 | −1.46 | −1.61 | −1.25 | −1.35 |
| 4 | −2.26 | −2.51 | −1.61 | −1.61 | −1.45 | −1.40 |
| 5 | −2.31 | −2.46 | −1.61 | −1.71 | −1.45 | −1.45 |
| 6 | −2.56 | −2.71 | −1.61 | −1.71 | −1.40 | −1.45 |
| 7 | −2.41 | −2.51 | −1.81 | −2.11 | −1.40 | −1.60 |
| 8 | −2.56 | −2.66 | −2.01 | −2.11 | −1.55 | −1.55 |
| 9 | −2.66 | −2.66 | −2.16 | −2.26 | −1.50 | −1.55 |
| 10 | −2.66 | −2.61 | −2.46 | −2.41 | −1.55 | −1.70 |
| 11 | −2.61 | −2.76 | −2.36 | −2.46 | −1.55 | −1.75 |
| 12 | −2.76 | −2.71 | −2.51 | −2.46 | −1.36 | −1.36 |
| 13 | −2.66 | −2.71 | −2.56 | −2.61 | −1.61 | −1.61 |
| 14 | −2.86 | −2.86 | −2.71 | −2.61 | −1.81 | −1.76 |
| 15 | −2.91 | −2.86 | −2.71 | −2.76 | −1.91 | −1.86 |
| 16 | −2.86 | −2.86 | −2.71 | −2.86 | −1.96 | −2.06 |
| 17 | −2.86 | −2.86 | −2.71 | −2.81 | −2.14 | −2.46 |
| 18 | −2.91 | −3.01 | −3.01 | −2.81 | −2.14 | −2.56 |
| 19 | −2.86 | −2.96 | −2.86 | −2.91 | −2.19 | −2.56 |
| 20 | | −2.96 | −3.11 | −3.01 | −2.39 | −2.56 |
| 21 | | | −2.91 | −3.01 | −2.39 | −2.56 |
| 22 | | | −2.96 | −2.91 | −2.44 | −2.66 |
| 23 | | | −3.11 | −3.06 | −2.54 | −2.76 |
| 24 | | | −3.01 | −3.06 | −2.54 | −2.66 |
| 25 | | | | | −2.79 | |
| 26 | | | | | −2.69 | |

to five prelight-, light- and dark-adaptation sequences were necessary. During one session, then, the dark-adaptation period of one run could serve as the prelight-adaptation period of the following run, experimental time, therefore, being minimized. Under no conditions, however, was *S* in the darkroom for a continuous period of longer than 1.5 hr. This meant that for the longer adaptation durations only one or two runs were possible in one session.

## Results

First, let us consider the acuity dark-adaptation function for a constant acuity and constant light-adaptation luminance. A parameter of this function investigated in this experiment was the duration of light adaptation (Tables 1, 2, and 3, and Fig. 2, 3, and 4). The experimental procedure followed in obtaining the data in Fig. 2, 3, and 4 varied only with respect to the acuity values of the grating used.

The following observations may be made with regard to these curves. They are generally similar in form to the acuity dark-adaptation curves obtained in previous studies (**1, 2**). They are steep during the early minutes of dark adaptation, and in some of these curves a break occurs which is usually explained in terms of the rod-cone duplicity theory described by Hecht (**4**).

The influence of light-adaptation duration as a parameter of the function in Fig. 2, 3, and 4 becomes evident in several ways: (*a*) the rod-cone break disappears for the shorter durations of light adaptation; (*b*) for

TABLE 2

Log Threshold Luminance in Millilamberts During Dark Adaptation After Different Durations of Light Adaptation
(Visual acuity = 0.083. *Ss* AD and AG)

| Time in Dark (min.) | Duration of Light Adaptation | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 Sec. | | 30 Sec. | | 5 Min. | | 10 Min. | |
| | AD | AG | AD | AG | AD | AG | AD | AG |
| 0.017 | −0.65 | −0.55 | −0.30 | 0.17 | 0.94 | 0.99 | 0.99 | 1.09 |
| 0.25 | −1.35 | −1.45 | −0.73 | −0.73 | 0.39 | 0.14 | 0.59 | 0.29 |
| 0.50 | −1.64 | −1.70 | −0.93 | −0.78 | 0.14 | −0.06 | 0.14 | −0.01 |
| 0.75 | −1.76 | −1.95 | −1.30 | −0.90 | 0.00 | −0.11 | −0.06 | −0.11 |
| 1 | −2.06 | −2.10 | −1.35 | −1.30 | −0.16 | −0.46 | −0.31 | −0.41 |
| 2 | −2.21 | −2.20 | −1.33 | −1.47 | −0.99 | −0.01 | −0.90 | −1.05 |
| 3 | −2.31 | −2.30 | −1.63 | −1.43 | −1.24 | −1.12 | −1.25 | −1.20 |
| 4 | −2.06 | −2.35 | −1.76 | −1.62 | −1.22 | −1.12 | −1.25 | −1.35 |
| 5 | −2.71 | −2.50 | −1.78 | −1.70 | −1.37 | −1.27 | −1.25 | −1.40 |
| 6 | −2.71 | −2.55 | −1.86 | −1.70 | −1.27 | −1.37 | −1.50 | −1.40 |
| 7 | −2.31 | −2.45 | −2.06 | −1.93 | −1.12 | −1.63 | | −1.40 |
| 8 | −2.86 | −2.45 | −2.16 | −1.90 | −1.42 | −1.72 | −1.60 | −1.40 |
| 9 | −2.51 | −2.50 | −2.31 | −2.10 | −1.32 | | −1.45 | −1.30 |
| 10 | −2.51 | −2.40 | −2.31 | −2.11 | −1.32 | −1.61 | −1.45 | −1.50 |
| 11 | | | | | | | −1.55 | −1.35 |
| 12 | −2.71 | −2.40 | −2.41 | −2.25 | −1.52 | −1.81 | −1.60 | −1.70 |
| 14 | −2.41 | −2.40 | −2.56 | −2.45 | −1.56 | −1.76 | −1.53 | −1.95 |
| 16 | −2.41 | −2.35 | −2.46 | −2.56 | −1.61 | −1.76 | −1.82 | −2.00 |
| 18 | −2.61 | | −2.61 | −2.65 | −1.95 | −2.00 | −2.01 | −2.16 |
| 20 | −2.71 | | −2.61 | −2.56 | −2.15 | −2.11 | −2.16 | −2.21 |
| 22 | −2.61 | | −2.81 | −2.71 | −2.15 | −2.00 | −2.16 | −2.46 |
| 24 | −2.61 | | −2.81 | −2.55 | −2.25 | −2.21 | −2.26 | −2.56 |
| 26 | | | −2.86 | | −2.30 | −2.05 | −2.31 | −2.51 |
| 28 | | | −2.91 | | −2.40 | −2.10 | −2.41 | −2.66 |
| 30 | | | | | −2.50 | −2.31 | −2.47 | −2.56 |

TABLE 3

LOG THRESHOLD LUMINANCE IN MILLILAMBERTS DURING DARK ADAPTATION AFTER DIFFERENT DURATIONS OF LIGHT ADAPTATION

(Visual acuity = 0.62. *Ss* AD and AG)

| Time in Dark (min.) | Duration of Light Adaptation | | | | | |
|---|---|---|---|---|---|---|
| | 1 Sec. | | 30 Sec. | | 5 Min. | |
| | AD | AG | AD | AG | AD | AG |
| 0.017 | 1.04 | 0.69 | 1.60 | 1.05 | 2.43 | 2.43 |
| 0.25 | 0.19 | 0.54 | 0.80 | 0.65 | 1.58 | 1.45 |
| 0.50 | −0.31 | 0.24 | 0.00 | 0.45 | 1.48 | 1.62 |
| 0.75 | −0.21 | 0.04 | 0.25 | 0.25 | 1.53 | 1.25 |
| 1 | −0.41 | 0.14 | 0.10 | 0.10 | 0.88 | 1.21 |
| 2 | −0.26 | −0.01 | −0.60 | −0.41 | 0.19 | 0.59 |
| 3 | −0.26 | −0.01 | −0.36 | −0.46 | 0.14 | 0.29 |
| 4 | −0.26 | −0.36 | −0.26 | −0.61 | 0.09 | −0.21 |
| 5 | −0.16 | −0.46 | −0.36 | −0.66 | 0.04 | −0.41 |
| 6 | −0.31 | −0.21 | −0.36 | −0.51 | −0.06 | 0.02 |
| 7 | −0.21 | −0.41 | −0.31 | −0.36 | 0.14 | 0.04 |
| 8 | −0.31 | −0.21 | −0.21 | −0.46 | 0.09 | −0.01 |
| 9 | −0.31 | −0.46 | −0.36 | −0.46 | −0.06 | −0.21 |
| 10 | −0.26 | −0.46 | −0.36 | −0.41 | −0.06 | −0.16 |
| 11 | −0.31 | −0.51 | −0.51 | −0.61 | 0.04 | −0.31 |
| 12 | −0.21 | −0.61 | −0.36 | −0.56 | −0.06 | −0.11 |
| 13 | | −0.76 | −0.41 | | −0.21 | −0.16 |
| 14 | | −0.71 | −0.56 | | −0.16 | |

shorter durations there is a shift of the rod-cone break toward the early portion of the dark-adaptation curves along the time axis, and the curves begin at lower threshold luminances and reach asymptotic levels more quickly; and (*c*) after 5 min. of light adaptation the variable has little or no effect up to 10 min. Apparently whether the curve actually reaches a constant level at exactly 5 min. cannot be determined from the data. The total change in threshold luminance, as the duration of light adaptation is changed from 1 sec. to 5 min., is between 1.5 and 2.0 log ml. in threshold.

With respect to differences between Fig. 2, 3, and 4, i.e., between the different gratings used, there does not seem to be much change in threshold-luminance values between a grating

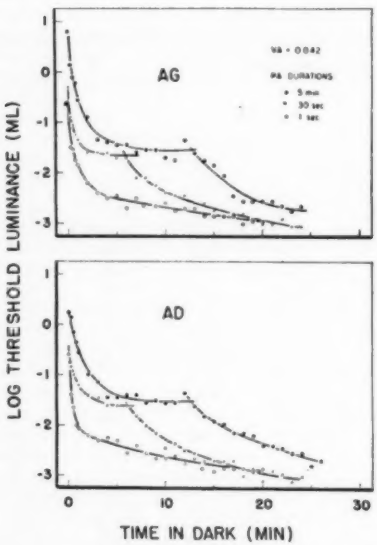


FIG. 2. Dark-adaptation curves for visual acuity (VA) = .042 following 5-min., 30-sec., and 1-sec. preadaptation (PA) to a constant luminance of 1000 ml. Subjects AG and AD.

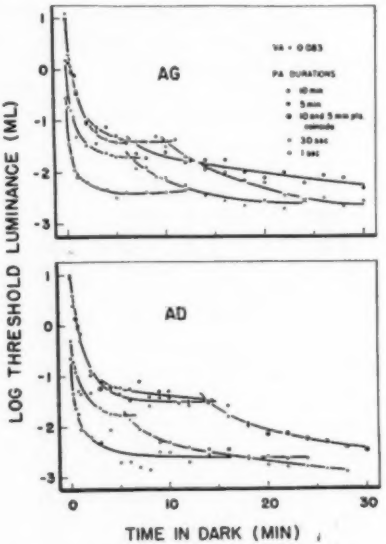


FIG. 3. Dark-adaptation curves for visual acuity (VA) = .083 following 10-min., 5-min., 30-sec., and 1-sec. preadaptation (PA) to a constant luminance of 1000 ml. Subjects AG and AD.

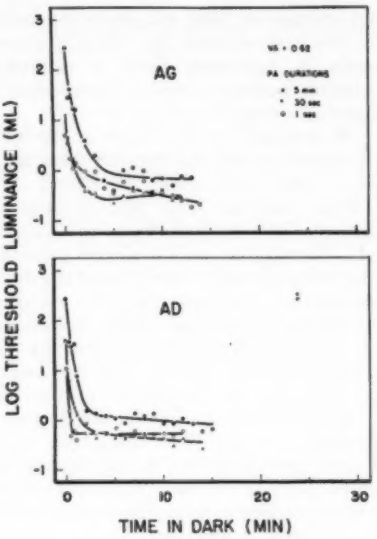


FIG. 4. Dark-adaptation curves for visual acuity (VA) = .62 following 5-min., 30-sec., and 1-sec. preadaptation (PA) to a constant luminance of 1000 ml. Subjects AG and AD.

of an acuity value of .083 and one of an acuity value of .042. However, a marked change occurs with the use of a grating of an acuity value of .62 (Fig. 4). This change is first evidenced in the disappearance of the rod-cone break. Further, it is seen that the differential effect upon threshold luminance of light-adaptation duration is minimized. There is a slight displacement towards lower threshold luminances when light-adaptation duration is reduced from 5 min. to 30 sec., but no appreciable further decrease in threshold-luminance level when light adaptation is reduced from 30-sec. to 1-sec. duration. Finally, the threshold luminance for the .62 grating during dark adaptation following all three light-adaptation durations is considerably higher than that for the .042 and .083 gratings.

Examination of the acuity parameter shows that during the early part of dark adaptation, as the acuity necessary to resolve the test object increases, the threshold luminance also increases. For a change in acuity from .042 to .083 this holds only at the higher light-adaptation durations. For a change in acuity from .083 to .62, however, the change in threshold luminance for resolution of the test object is marked for all light-adaptation durations, constituting, on the average, an increase of approximately 1.5 log ml.

## DISCUSSION

These results agree essentially with previous measurements of dark adaptation following different durations of light adaptation. Despite important differences in procedure and in criterion of threshold, the dark-adaptation process is found to respond in much the same way to an increase in the period of light adaptation. Two effects are generally characteristic: As the exposure to light of a constant luminance lengthens, (*a*) the initial threshold rises; and (*b*) the speed of dark adaptation decreases. A third effect occurs when the threshold criterion is sufficiently low to permit rod response. In this case the longer the pre-exposure, the more prominent is the primary cone dark adaptation and the more delayed is the secondary rod adaptation.

With respect to the relation between duration of light adaptation and the speed of subsequent dark adaptation, a comparison of the 1-sec. function with the other curves in Fig. 2 and 3 is illustrative. Dark adaptation for the lower acuity levels is very much more rapid following 1 sec. of irradiation than it is following longer exposures. The 1-sec. curve reaches a constant minimum within about 12 min., while curves for the longer durations are still incomplete after 30 min. in the dark.

The change in rate of dark adaptation was shown by Haig (**3**) and by Wald and Clark (**8**) to apply to rod dark adaptation

exclusive of cone functioning. Haig identified two components in this change of rate, a decrease in the slope of the function, and a displacement to the right on the time axis. With increasing preadaptation, the latter effect is evident in the curves of Fig. 2 and 3. The rod portions of these curves are displaced increasingly to the right on the time axis as duration of preadaptation increases. The alteration in slope of the dark-adaptation functions is less clear. Following exposures to light longer than 1 sec. the early portions of rod dark adaptation are hidden behind the cone function, and changes in velocity of rod adaptation cannot be detected. More data following lower luminances of the adapting light are needed in order to obtain a sufficient number of purely rod functions for comparison.

While our experiment does not permit a definite answer to the question of the relative influence of duration and luminance of preadaptation upon the dark-adaptation process for different acuities, the effects of varying duration appear very similar to the effects of varying luminance shown by Brown (2). In general, the initial thresholds are lower, and the time required for complete dark adaptation decreases rapidly as either the luminance or the duration of the preadapting light decreases. With regard to the form of the acuity dark-adaptation curves, the influence of both duration and luminance of pre-exposure is most marked during the early stage of dark adaptation. Progressively less effect appears as time in the dark increases. In our data the disappearance of a definite rod-cone break after brief exposures to light parallels Brown's finding for low luminances. However, a strict comparison of the portions of the two studies in which the total quantity of previous light adaptation was the same, but of lower luminance and longer duration in one case, higher luminance and shorter duration in the other, yields a discrepancy. No rod-cone breaks were found by Brown following 5 min. exposure to 100 ml. (and lower). Our curves for the same acuity (.042), using 30 sec. of preadaptation at 1000 ml., show the break in the case of both *S*s, This is apparently a departure from a reciprocal relation between time and luminance of light adaptation.

With regard to the effect of the level of visual acuity, the present data agree very well with those of Brown (2). Taken together with the findings of Brown, Graham, Leibowitz, and Ranken (1), these three studies clearly establish the independence of the form of the dark-adaptation function from the criterion of threshold. Visual acuity determines the level of luminance covered by the dark-adaptation curve. As the acuity required for the resolution of the test object increases, the curves are displaced upward on the log luminance axis. Curves corresponding to the higher degrees of acuity represent cone functioning only, and drop to a final level after about 5 to 12 min. in the dark.

## Summary

Dark-adaptation curves representing three levels of visual acuity have been determined following preadaptation for from 1 sec. to 10 min. to a constant luminance of 1000 ml.

1. At all acuity levels the initial thresholds rise, and the speed of dark adaptation decreases as duration of preadapting light increases from 1 sec. to approximately 5 min. These effects are less pronounced at the highest acuity investigated, .62. A threshold response at this level represents cone adaptation exclusively.

2. At lower acuities, .083 and .042, an additional effect occurs as a function of duration. The shorter the period of light adaptation, the less prominent is the primary cone dark adaptation, and the sooner does the rod dark adaptation appear.

3. Duration of light adaptation has a marked effect upon the level of threshold luminance early in the course of dark adaptation. The effect becomes progressively reduced as time in the dark increases.

4. As the level of acuity increases, the threshold luminance also increases, depending upon the amount of change in acuity and the preadapting duration.

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# FOVEAL SIMULTANEOUS CONTRAST AS A FUNCTION OF INDUCING-FIELD AREA[1]

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Simultaneous brightness contrast is a visual phenomenon occurring when two illuminated visual fields are placed side by side; contrast may be observed as a change in the apparent brightness in either of the fields. The field on which we discriminate this change may be termed the test field. The adjacent field may be called the inducing field.

Several parameters have been found important in the contrast phenomenon. The contrast effect, or inhibition of the test-field apparent brightness was found to (*a*) increase with an increase in inducing-field luminance (**1, 2, 4**); (*b*) decrease with an increase in the spatial separation between the test and inducing fields (**2, 4**); and (*c*) increase with an increase in inducing-field area.[2]

With respect to this last parameter, inducing-field area, the above cited data were obtained over a relatively small range of inducing-field luminances. The present investigation is intended to extend the previous data. That is, the apparent brightness of the test field as a function of inducing-field area is studied over a relatively large range of inducing-field luminances ($-\infty$ to 2.71 log ml.).

Before proceeding to the specific design of this investigation, however, we must consider a question of experimental control, specifically of the parameter of spatial separation between test and inducing fields. Obviously, the control of spatial separation depends upon its definition; but this definition varies markedly in the literature.

For example, Leibowitz, Mote, and Thurlow (**4**) measured spatial separation as the distance separating the near borders of the test and inducing fields. This definition is illustrated in Exp. I (see Fig. 1B) of the present paper. The area of the inducing field (*i*) is increased by the extension of its upper border, while its lower border is fixed adjacent to the test field (*t*). According to Leibowitz, Mote, and Thurlow, then, spatial separation in Exp. I may be considered as constant.

Fry and Alpern (**2**), on the other hand, measured spatial separation as the distance between the centers of the test and inducing fields. Experiment II (Fig. 1B) of the present paper illustrates this definition of spatial separation. The area of the inducing field is increased by extension of both upper and lower borders, while the distance between the centers of the test and inducing fields is held constant. According to Fry and Alpern, therefore, spatial separation in Exp. II may be considered as held under control.

Which procedure yields the "true" relationship between test-field apparent brightness and inducing-field area, i.e., which controls the effective parameter of spatial separation? A consideration of the combined geometric and contrast relations between the test and inducing fields might be helpful in this connection.

[1] This work was supported in part by a research grant NSF-G923 from the National Science Foundation and in part by the Graduate School of Northwestern University.

[2] G. A. Fry and M. A. Alpern. Personal communication. June, 1952.

We can describe each field as being composed of a number of elemental areas; each inducing elemental area can be termed $\Delta a_i$, and each test elemental area, $\Delta a_t$. Further, it may be assumed according to previous experiments (**2, 4**) that each $\Delta a_i$ has a contrast effect, $\Delta H_i$, upon each $\Delta a_t$, the effect being directly proportional to $\Delta a_i$, and inversely proportional to the distance, $r$, separating $\Delta a_i$ from $\Delta a_t$.

Then

$$\Delta H_i = K\left(\frac{\Delta a_i}{r}\right) \qquad [1]$$

and, therefore

$$H_i = K\sum\left(\frac{\Delta a_i}{r}\right) \qquad [2]$$

If we now consider the variation of the inducing-field area at an elemental level, it is obvious that as we increase area we add new $\Delta a_i$ elements at new $r$ distances to any one $\Delta a_t$ element—except for that $\Delta a_i$ at a point central to a circular path along which new $\Delta a_i$ elements might be added to the inducing field. Thus, at the elemental level, the only situation in which we can change inducing-field area without varying its distance from the test field is that in which the test field is a point central to a circular path along and within which the inducing-field area is being varied. The test field, of course, is not a point, so that it seems we cannot vary the inducing-field area without concomitantly varying the spatial separations between the elements of the test and inducing fields.

Suppose, however, that we attempt to control spatial separation at the "field" level such that even though individual $r$ values between $\Delta a_i$ and $\Delta a_t$ elements are varying, the average $r$ will remain constant. This might be accomplished in several ways.

First, we could add, for every distant $\Delta a_i$ element, one that would be near to the test field in such a way that the average or mean $r$ would remain the same. This, of course, requires a knowledge of the empirical contrast relationship between $H_i$ and $r$, in Equation *2*, since we would want to keep the effective mean $r$ constant. That is, if at the empirical level $H_i$ is a linear function of $r$, we would use an arithmetic mean to average out $r$ variation; if it is logarithmic, we would use a geometric mean, and so on.

This means that the success of such a statistical control depends upon an accurate prediction, for a particular $S$, of the nature of the $H_i$ vs. $r$ relationship. Unfortunately, we are not able to make such a prediction, since according to previous findings (**2**), variation in this relationship is marked between *S*s, and for one $S$ from day to day. It seems then that a statistical control is not feasible.

An alternative "field" approach would involve a circular test field and an inducing field that would be increased in area in a circular path concentric with the test field. In this way, even though the $r$ values to a single $\Delta a_t$ element might vary, the total of the $r$ values to all $\Delta a_i$'s (and whatever average thereof we might choose) would remain constant. The trouble with this method becomes apparent if we consider that the total contrast effect, $H_i$, is not distributed equally over the test field because of its inverse dependence upon $r$; the centroid of the effect would therefore shift within the test field as the inducing-field area is increased in circular fashion. Conceivably, this shift in the centroid could affect judgments of the test-field apparent brightness, especially when the inducing field is small relative to the test field.

Since both at an elemental and a "field" level the separation of the inducing-field area variable from the spatial separation variable seems at best approximate, the present experiment will consider both variables together. Or if we use the term $C_i$ to represent the combined effects of inducing-field area and spatial separation, we can generally state that

$$C_i = \sum\left(\frac{\Delta a_i}{r}\right) \qquad [3]$$

and, therefore, from Equation 2

$$H_i = KC_i. \qquad [4]$$

Thus, Equation 4 represents the relation of $H_i$ to $C_i$ under all conditions of inducing-field area variation.

Once we have determined the nature of Equation 4, we can test it in two ways: (*a*) We can see how it holds from one *S* to the next. Under "Discussion" below, Equation 4 is developed in detail and fitted to the data of the two *S*s in Exp. I. (*b*) We can see how our data vary from one type of inducing-area variation to the next (from Exp. I to Exp. II in Fig. 1B.) On the assumption that our reasoning is correct, Equation 4 should predict the data of one *S* taken under the different conditions of inducing-area variation from Exp. I to II. That is, since the same *S* is used from Exp. I to II, and since the differences between these experiments concerning inducing-area variation are allowed for in the calculation of $C_i$, then Equation 4, while retaining the same mathematical properties (including the same constants specific to one *S*), should predict the empirical differences resulting from the procedural differences from Exp. I to II.

These expectations are tested with a general experimental design common to both experiments (see Fig. 1B). To *S*'s right eye is presented a test field (*t*), a rectangle twice as wide as it is long; above the test field is the inducing field (*i*), equally as wide as the test field but variable in height, and thus in area. To *S*'s left eye is presented the match field (*m*), equal in size to the test field. The contrast effects of inducing fields of different areas can thus be determined from the equality brightness match between the match and test fields. In this way, the apparent brightness of the test field is measured as a function of inducing-field area over nine inducing-field luminances.

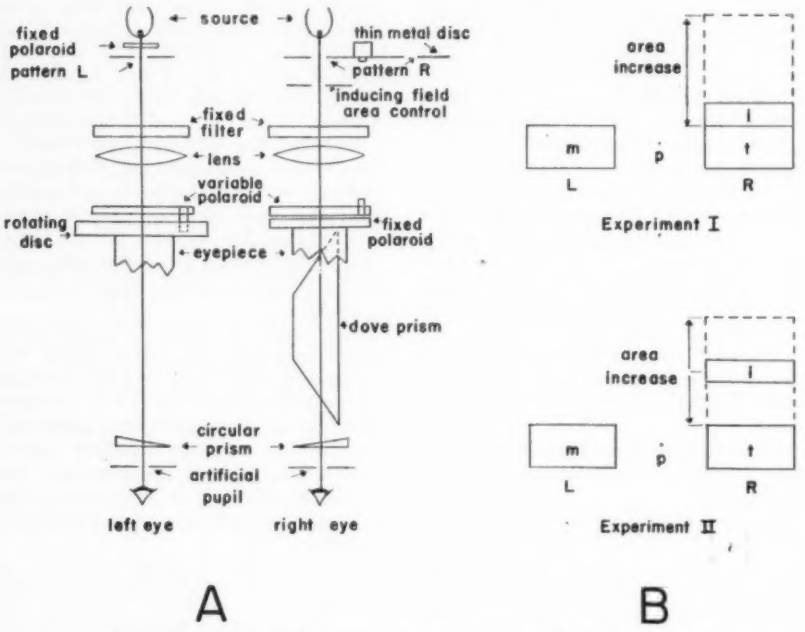


FIG. 1. (A) Schema of apparatus. (B) The binocular view and manner of inducing-field area variation in Exp. I and II.

## Experiment I

*Apparatus.*—A modification of the apparatus used by Diamond (1) is employed in the present experiment. The patterns seen by *S* are different for each eye (see Fig. 1B). One pattern, presented to the right eye only, includes: (*a*) a test-field rectangle (*t*), 33′ in visual angle along the horizontal and 16.5′ along the vertical; (*b*) adjacent to and above the rectangle, an inducing-field rectangle (*i*) also 33′ wide, but variable in its vertical extent from zero to 33′ (the inducing-field area can thus be varied from less than, to greater than, that of the test field); (**r**) a small fixation point located 21′ to the left of the test field. This point is also presented to *S*'s right eye only. The second pattern, presented to the left eye only, includes: (*a*) match-field rectangle (*m*), equal in size to the test field; and (*b*) a small fixation point located 21′ to the right of the match field.

In the binocular view (Fig. 1B) *S* is instructed to fuse left- and right-eye fixation points into one point, *P*, so that the match, test, and inducing fields are held in constant position relative to one another. Stimulation may be considered essentially foveal since the visual angle between the fused fixation point and furthest corner of any field is never more than 70′.

The right- and left-eye patterns are presented to *S* along two separate optical paths, one to each eye (Fig. 1A). The light source of each path is a 150-w. tungsten filament projection lamp, in front of which is a section of heat-absorbing glass. The light, diffused by flash opal glass, travels through its particular pattern (L or R). The luminance in either path can be continuously varied by fixed filters and a fixed and movable Polaroid. Made parallel by 4-diopter lenses, the light finally travels through 3-mm. artificial pupils into the eyes of *S* who is seated in a light-tight cubicle. The entire left optical path is adjustable horizontally for interpupillary distance by means of a screw arrangement attached to the optical bench.

Luminance controls are arranged independently in each of the two optical paths. In the path leading to *S*'s right eye, 10 identical patterns (of a test-field rectangle adjacent to and below an inducing-field rectangle) are cut in the thin metal disc which can be rotated and set so that each pattern falls directly before a diffuse light source. Neutral Wratten gelatin filters are mounted behind the inducing fields of either of these patterns; the inducing field of one pattern is of zero density and that at the other extreme is completely blacked out. The luminance of the inducing field in this way can be varied in discrete steps over a range of greater than 500 ml. A Dove prism, moreover, set in the optical pathway, enables the optical inversion of the pattern so that the field behind which the gelatin filter is mounted now appears as the test field. The optical inversion also requires a readjustment of the dimensions of the two fields at the thin metal disc. The "new" test field must be fixed in dimension into a rectangle 33′ wide by 16.5′ high, and also the new inducing field must be made into a rectangle 33′ wide and variable in vertical extent. The test field, therefore, may also be varied in luminance over an equally wide range. For the field behind which the gelatin filter does not appear (depending upon the position of the Dove prism) the luminance may be varied by means of fixed filters and a pair of Polaroids, one of the pair fixed, the other rotatable.

The luminance of the match field in the left optical path is controlled in the following manner: Between the diffuse light source and pattern is a small Polaroid disc which just covers the match field, but not its fixation point. The disc serves as the fixed member of a pair of Polaroids; the variable member is coupled to a metal disc which *S* can rotate about the left eyepiece. As *S* varies the luminance of the match field, therefore, the fixation-point luminance remains constant. The luminance of both the match field and its fixation point are simultaneously changed by fixed filters. The luminance of the match field is indicated by the combined densities of the fixed filters and Polaroids.

The luminances of the match, test, and inducing fields were calibrated by means of binocular matches to fields of similar shapes and areas and whose luminances had been determined by a MacBeth Illuminometer. The maximum luminances of the match, test, and inducing fields were 1178 ml.

Inducing-field area is controlled as follows: Just in front of the thin metal disc, i.e., toward *S*, a blackened razor blade, mounted on a micrometer assembly, can be moved across the inducing field. It can be so moved that when the razor-blade edge coincides with the edge of the test field, the inducing-field area is zero. As the razor-blade edge is drawn away from the edge of the test field, the inducing-field area increases in successive rectangular increments. The inducing-field area can thus be controlled by the adjustment of the micrometer assembly, on which is indicated the vertical dimension of the area (the horizontal being constant). The horizontal dimension is fixed at 33′ and the vertical dimension variable from zero to 33′.

Two further additions to the apparatus are intended to reduce the variability of the data.

The first is concerned with enabling *S* more easily to fuse the left- and right-eye fixation

points. A circular prism, the refracting angle of which is 5°, is placed in each eyepiece in a manner such that by rotating each eyepiece *S* can optically move both left- and right-eye patterns in circular paths. By moving one clockwise and the other counterclockwise, *S* can move each laterally with respect to the other and thus attain fusion more easily.

A check was made to determine whether rotation of the prisms affected the apparent brightnesses of left- and right-eye visual fields. Each of the prisms was set at four points of rotation, i.e., 3, 6, 9, and 12 o'clock, such that all possible combinations of these positions between the two prisms were effected. At each prism-position combination, matches were made between the test and match field. No significant or systematic differences were found as a result of prism rotation.

Another modification concerns the artificial pupils. It was found that the variability, introduced into the data by slight head movements of *S* behind the artificial pupils, could be reduced if the artificial pupils were attached to *S*'s head. Optician's trial frames are therefore used which allow both vertical and horizontal adjustment of the artificial pupils such that they can be set directly into line with *S*'s own pupils.

*Method.*—The experimental method was designed to investigate the apparent brightness of the test field as a function of the inducing-field area; the area was varied in seven steps, the inducing-field vertical dimension varying from zero to 33′. This entire area function was then studied for eight inducing-field luminances from zero to 2.71 log ml. The test-field luminance was held constant at .60 log ml. during the entire experiment.

Each experimental session was thus devoted to obtaining the area function for a constant inducing-field luminance. Seated in the light-tight cubicle, *S* initially dark adapted for 3 min., then light adapted for 3 min. to the binocular view, i.e., at a test-field luminance of .60 log ml., the match field at the same apparent brightness as the test field, the inducing field at a luminance set for a particular session, and the inducing-field area set for a particular experimental point. The *S* then began making brightness-equality matches following the psychophysical method of adjustment as described by Guilford (**3**). That is, *S* set the luminance of the match field so that it appeared equal to that of the test field. The *E* then changed the luminance of the match field in a random manner after each match. The *S* had to adjust the match-field luminance again until it seemed equal in apparent brightness to that of the test field. In this manner *S* made five practice and five experimental matches at each of seven inducing-field areas, the inducing-field luminance being held constant during one experimental session.

It was found with this procedure that each experimental point (taken at a constant inducing-field area and luminance) could be measured independently. That is, no significant differences in the results occurred whether *S* remained in the darkroom while making 10 matches to each of seven inducing-field areas or whether he came out of the darkroom after each set of 10 matches. As long as 3-min. dark adaptation and a 3-min. light adaptation preceded

TABLE 1

TEST-FIELD APPARENT BRIGHTNESS ($B_m$) AS A FUNCTION OF INDUCING-FIELD AREA ($C_i$) FOR DIFFERENT INDUCING-FIELD LUMINANCES ($B_i$)

(Data are in log millilamberts and for two *S*s)

| Inducing-Field Luminance (Log $B_i$) | Vertical Height of Inducing Field (Min.)* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | | 5.5 | | 11.0 | | 16.5 | | 22.0 | | 27.5 | | 33 | |
| | AD | JR | AD | JR | AD | JR | AD | JR | AD | JR | AD | JR | AD | JR |
| $-\infty$ | .60 | .60 | .58 | .60 | .59 | .63 | .62 | .60 | .61 | .59 | .63 | .58 | .59 | .59 |
| −1.51 | .63 | .56 | | | | | .59 | .53 | | | | | .54 | .48 |
| −0.43 | .57 | .64 | | | | | .60 | .57 | | | | | .60 | .61 |
| 0.06 | .56 | .59 | .63 | .49 | .64 | .55 | .58 | .64 | .56 | .51 | .65 | .60 | .59 | .64 |
| 0.60 | .63 | .60 | .63 | .44 | .59 | .45 | .57 | .51 | .60 | .49 | .51 | .40 | .51 | .32 |
| 1.14 | .60 | .60 | .57 | .39 | .49 | .24 | .57 | .33 | .44 | .28 | .42 | .34 | .45 | .16 |
| 1.63 | .61 | .59 | .35 | .05 | .36 | .14 | .26 | −.01 | .27 | −.09 | .21 | −.27 | .18 | −.30 |
| 2.16 | .60 | .59 | .30 | −.04 | .03 | −.10 | −.01 | −.13 | −.01 | −.20 | .15 | −.41 | .02 | −.32 |
| 2.71 | .57 | .53 | .18 | −.12 | −.01 | −.35 | −.10 | −.49 | −.13 | −.47 | −.12 | −.56 | −.19 | −.59 |

* This indicates inducing-field area.

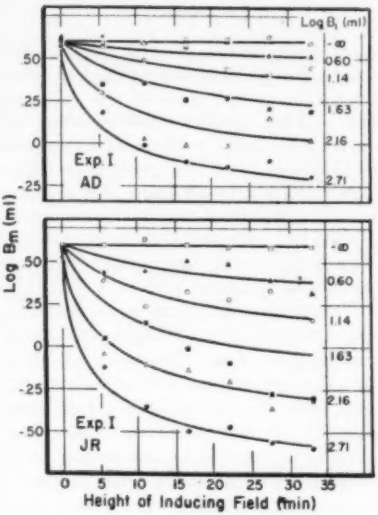


FIG. 2. Apparent brightness of the test field as a function of inducing-field area and luminance, separately graphed for each *S*.

each set of matches, each experimental point could be measured in independent fashion.

In each set of 10 matches the average of the five experimental match-field luminances was taken as the measure of the apparent brightness of the test field at each value of the inducing-field area. The above procedure was followed for eight inducing-field luminances and for two *S*s, AD and JR.

*Results.*—The data are presented separately for each *S* in Table 1 and Fig. 2. Figure 2 shows the luminance of the match field ($B_m$) plotted as a function of the inducing area (as measured by its vertical dimension). $B_m$ may be termed the apparent brightness of the test field since its value is based upon an equality judgment between the match- and test-field apparent brightnesses. The function is graphed for different values of inducing-field luminance.

The effect of inducing-field area upon test-field apparent brightness is nonlinear, being a negatively accelerated decreasing function. As the inducing-field area is increased, the test-field apparent brightness falls sharply at first, then levels off, possibly to an asymptotic value. This holds true when the inducing-field luminance has a measurable effect upon the test-field apparent brightness. That is, below an inducing-field luminance value of .60 log ml., an increase in area has no measurable effect upon test-field apparent brightness. Above .60 log ml., however, the greater the inducing-field luminance the greater the depression of the test-field apparent brightness. These findings with respect to inducing-field luminance are in agreement with those in an earlier study (1).

Although the magnitude of the depression of test-field apparent brightness is greater for JR than AD, the curves are fitted by the same mathematical expression. The assumptions underlying these fits are discussed later.

## EXPERIMENT II

*Apparatus.*—The apparatus is the same as in Exp. I, except for a change in the control of the inducing-field area. This change is such as to permit variation of inducing-field area while the distance between the centers of the inducing and test fields remains constant. (In Exp. I, the center of the inducing field moves away from the test field as the inducing-field area is increased.)

The inducing-field area is controlled by the use of thin metal masks in which are cut various rectangles of the same width as the test field but of different heights. These rectangles mask the inducing-field openings in the thin metal disc (the disc described in Fig. 1A and in the "Apparatus" section in Exp. I) such that even though their areas differ, their centers remain at a constant distance from the center of the test field. Thus by mounting the different masks over the inducing-field openings in the thin metal disc, *E* can vary the area of the inducing field while holding constant the distance of its center from that of the test field.

*Method.*—The method and procedure were identical to that followed in Exp. I and involved one *S*, AD.

TABLE 2

TEST-FIELD APPARENT BRIGHTNESS ($B_m$) AS A FUNCTION OF INDUCING-FIELD AREA ($C_i$) FOR DIFFERENT INDUCING-FIELD LUMINANCES ($B_i$)

(Data are in log millilamberts and for one *S*)

| Inducing-Field Luminance (Log $B_i$) | Vertical Height of Inducing Field (Min.)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 5.5 | 11.0 | 16.5 | 22.0 | 27.5 | 33 |
| $-\infty$ | .63 | .60 | .59 | .60 | .66 | .54 | .58 |
| .60 | .59 | .64 | .60 | .68 | .61 | .51 | .57 |
| 1.14 | .60 | .65 | .63 | .67 | .49 | .47 | .37 |
| 1.63 | .57 | .56 | .47 | .47 | .37 | .30 | .31 |
| 2.16 | .61 | .56 | .31 | .24 | .00 | .07 | .12 |
| 2.71 | .58 | .47 | .19 | .07 | −.13 | −.17 | −.23 |

* This indicates inducing-field area.

*Results.*—The results are summarized in Table 2 and Fig. 3. Figure 3 graphs the same variables as are presented in Fig. 2. The curves drawn through the points are based upon theoretical assumptions to be discussed later.

The curves in Fig. 3 resemble those in Fig. 2 in every respect but one. Specifically, the acceleration of the curves in Fig. 3 is considerably less than that of the curves in Fig. 2. In other words, the test-field apparent brightness is relatively less affected by the smaller inducing-field areas in Exp. II than in Exp. I.

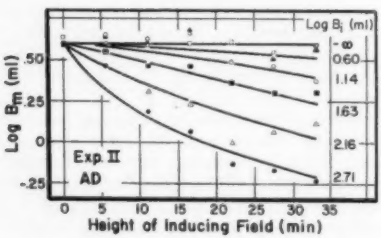


FIG. 3. Apparent brightness of the test field as a function of inducing-field area and luminance for one *S*.

## DISCUSSION

According to the results, the test-field apparent brightness is inhibited in direct proportion to the area of the inducing field. This general relationship, of course, is assumed in the basic hypothesis of this paper, and is expressed in Equations 3 and 4. In addition, it is assumed that the experimental control of spatial separation, between test and inducing fields, is at best an approximation during variation of inducing-field area, such that both spatial separation and inducing-field area are theoretically considered together. It now remains to develop from these equations a formulation into which may be inserted the actual operations of the above experiments.

First, we should mention our basic assumptions concerning the apparent brightnesses of the test and match fields (these were equated by *S*), or any field in general. These are that the apparent brightness of a field is: (*a*) directly proportional to the field's luminance, $B$, raised to some power, $a$; and (*b*) inversely proportional to an inhibiting activity, $H$, which activity somehow depends upon light stimulation (within the field itself or in the surround of the field) and is therefore proportional to the luminance of the stimulating light, or

$$H = kB. \qquad [5]$$

These first two assumptions have already been made and supported empirically in a previous experiment (**1**, p. 312).

A third assumption, specific to the present experiment, is that the inhibitory activity contributed particularly by the inducing field, $H_i$, is proportional not only to the luminance of the inducing field ($B_i$) raised to some power $b$, but also to $C_i$ (the parameter representing not only area but also the spatial separation) raised to some power, $c$. Thus:

$$H_i = kB_i^b C_i^c. \qquad [6]$$

Finally, if we equate match- and test-field apparent brightnesses, as did *S* in

the actual experiment, then

$$\frac{B_m^{a_1}}{k_1 B_m} = \frac{B_t^{a_2}}{k_2 B_t + k_3 B_t^b C_i^c} \qquad [7]$$

and since our measures are in logarithmic form,

$$\log B_m = \frac{a_2 \log B_t - \log (k_2 B_t + k_3 B_t^b C_i^c) + \log k_1}{a_1 - 1}. \qquad [8]$$

Our last task now is to calculate the experimental values of $C_i$ according to Equation 3. Upon the assumption that the inhibitory activity contributed by the inducing field involves stimulation of the retina, it would seem fruitful to choose as our inducing-field elemental area, $\Delta a_i$, the area defined by a single retinal element, i.e., the area within the cross section of a single cone. According to Polyak (**5**), the average foveal cone is about 24″ in diameter. This means there are approximately 68,063 $\Delta a_i$'s in the inducing field at its maximum and 34,032 $\Delta a_i$'s in the test field.

We can then solve for $\sum \left(\frac{\Delta a_i}{r}\right)$ (a graphic solution is used in the present experiment) for each of the vertical heights of the inducing field, in both Exp. I and II. The resulting values are given in Table 3. The values of the constants are determined separately for each $S$ with the same method of fitting the data as employed by Diamond (**1**, p. 312).

Inserting these, and the appropriate inducing-field luminance ($B_i$) values into Equation 8, we obtain theoretical values for log $B_m$ which determine the curves drawn in Figs. 2 and 3.

As hypothesized the formulation generally fits the data of the two $S$s, the values of the constants being somewhat different for each $S$. Further, it predicts the results obtained from two different methods of varying the inducing-field area. That is, the constants in Equation 8 for AD remain the same from Exp. I to II. The differences in the theoretical curves in Figs. 2 and 3 are therefore due entirely to differences in the variation of inducing-field area.

The results then are consistent with previous data and would seem to indicate the experimental and theoretical fruitfulness of taking into account the fact that spatial separation, between the test and inducing fields, varies with the variation in area of the inducing field.

TABLE 3

THEORETICAL VALUES FOR $C_i$ AND CONSTANTS IN EQUATION 8

| $C_i$ Values | | | Constant Values | | |
|---|---|---|---|---|---|
| Inducing-Field Height (Min.) | Experiments | | Constants | $S$s | |
| | I | II | | AD | JR |
| 0 | 0 | 0 | $a_1 = a_2$ | 3.0 | 3.0 |
| 5.5 | 2637 | 979 | $k_1 = k_2$ | .0174 | .0174 |
| 11.0 | 4171 | 1984 | $k_3$ | .0028 | .0073 |
| 16.5 | 5283 | 3059 | $b$ | .90 | .98 |
| 22.0 | 6157 | 4245 | $c$ | 1.36 | 1.53 |
| 27.5 | 6884 | 5619 | log $B_t$ | .60 | .60 |
| 33.0 | 7507 | 7507 | | | |


## SUMMARY

The apparent brightness of a 33′ test-field square is studied as a function of the area and luminance of an inducing-field square, the area varying from zero to double that of the test field. A binocular matching technique is used in two experiments. These differ in the method of holding constant the spatial separation between the test and inducing fields while the inducing-field area is varied. Experiment I holds constant the distance between the near borders of the two fields. Experiment II holds constant the distance between their centers. It is pointed out that neither method of spatial-separation control is justified and that it is theoretically more correct to assume that, along with inducing-field area variation, spatial separation is also being varied.

The results for both experiments show that the test-field apparent brightness decreases as the area of the inducing field increases, but only for inducing-field luminance equal to or greater than the test-field luminance. In Exp. II, the test-field apparent brightness is relatively less affected by the smaller inducing-field areas than in Exp. I, although the effect is the same for the largest area.

An equation, expressing the relation between test-field apparent brightness and inducing-field luminance and area, is developed. This equation is based upon the assumption that spatial separation varies concomitantly with inducing-field area. A satisfactory fit is obtained for the data of both experiments.

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